DOI: 10.1007/s002679910039

Irrigated Agriculture and Wildlife Conservation: Conflict on a Global Scale

A. DENNIS LEMLY*
United States Forest Service
Southern Research Station
Coldwater Fisheries Research Unit
Department of Fisheries and Wildlife Sciences
Virginia Tech University, Blacksburg, Virginia 24061-0321, USA

RICHARD T. KINGSFORD
New South Wales National Parks and Wildlife Service
P.O. Box 1967
Hurstville, New South Wales 2220, Australia

JULIAN R. THOMPSON
Wetland Research Unit
Department of Geography
University College London
London WC1H OAP, United Kingdom

ABSTRACT / The demand for water to support irrigated agriculture has led to the demise of wetlands and their associated wildlife for decades. This thirst for water is so pervasive that many wetlands considered to be hemispheric reserves for waterbirds have been heavily affected; for example, the California and Nevada wetlands in North America, the Macquarie Marshes in Australia, and the Aral Sea in central Asia. These and other major wetlands have lost most of their historic supplies of water and some have also experienced serious impacts from contaminated subsurface irrigation drainage. Now mere shadows of what they once were in terms of biodiversity and wildlife production, many of the so-called "wetlands of international importance" are no longer the key conservation strongholds they were in the past. The conflict between irrigated agriculture and wildlife conservation has reached a critical point on a global scale. Not only has local wildlife suffered, including the extinction of highly insular species, but a ripple effect has impacted migratory birds worldwide. Human societies reliant on wetlands for their livelihoods are also bearing the cost. Ironically, most of the degradation of these key wetlands occurred during a period of time when public environmental awareness and scientific assertion of the need for wildlife conservation was at an all-time high. However, designation of certain wetlands as "reserves for wildlife" by international review boards has not slowed their continued degradation. To reverse this trend, land and water managers and policy makers must assess the true economic costs of wetland loss and, depending on the outcome of the assessment, use the information as a basis for establishing legally enforceable water rights that protect wetlands from agricultural development.

Irrigation is essential to support agricultural production in many arid and semiarid regions of the world. However, there is often an important trade-off. The benefits from irrigation are offset by environmental costs, particularly to wetlands and wildlife. The intensive cultivation practices typically used in modern agriculture—as well as the underlying profit motive—place high demands on water supplies and put a premium on arable land. As a consequence, native wetlands can be eliminated in a short period of time (Frayer and others 1989, Moore and others 1990). Wetlands can be lost due to draining and direct conversion to agricultural land or because water removal from rivers and streams for use in irrigation robs wetlands of their source of water, and they simply dry up. In the western United States, for example, wetland losses due to agriculture are severe, exceeding 90% in many locations, and have been occurring virtually unimpeded for the past 100 years (Preston 1981, Reisner 1986, Thompson and Merritt 1988).

In addition to direct loss of wetland acreage, wetlands can be functionally lost due to contamination of the water supplies from agricultural pesticides and herbicides in surface runoff from irrigated fields (Roe and others 1980, Nell 1987, Moore and others 1990). Another important source of contamination was identified in the United States in the early 1980s—subsurface irrigation drainage. Irrigation water trapped by shallow clay lenses must be removed or drained or else it waterlogs the root zone and kills crops. The resultant drainage contains elevated concentrations of soil trace elements, salts, and other constituents and ultimately

KEY WORDS: Agricultural irrigation; Wetlands; Wildlife conservation; Water policy; Environmental economics; Ecosystem management

*Author to whom correspondence should be addressed.

© 2000 Springer-Verlag New York Inc.

reaches major wetlands, streams, and rivers (Moore and others 1990). Fish and wildlife populations have been poisoned by drainwater contaminants at several locations (Lemly and others 1993, Lemly 1994a, Presser 1994, Presser and others 1994). Thus, although agricultural-related reductions in water supplies have caused the demise of wetlands for centuries, there are more recent threats that are just now being identified and investigated. The implication of these threats on a global basis is serious (Lemly 1994b, 1996) and underscores the severity of the irrigation/wildlife dilemma. One thing is certain—finding an environmentally acceptable balance for irrigated agriculture is more complicated, yet more necessary, than ever before.

Because such a small portion of historic wetlands now remain in most arid and semiarid regions, they are especially valuable as wildlife habitat, both as refuges for resident wildlife populations and as stopovers and wintering/breeding grounds for migrating waterfowl and shorebirds (Frayer and others 1989). These wetlands constitute the last stronghold for remnant populations of endangered and threatened wildlife, plants, and fishes, whose survival as species hangs by a precarious hydrological thread that is all too easily cut by irrigated agriculture (Schroeder and others 1988, Stephens and others 1988, Hoffman and others 1990). In some locations the wetlands are valuable archaeological sites and have been used to identify and trace human occupancy and culture dating back several thousand years (Raven and Elston 1988, 1989, 1990). Wetlands continue to play key roles in supporting many human populations through their varied functions, products, and attributes (e.g., Dugan 1990).

Many of the world's key wetlands have been recognized for the wildlife conservation benefits they provide. For example, international scientific review boards and political leaders have espoused these benefits and called for protection of wetlands through such prominent efforts as the Ramsar Convention and the Rio Conference (Denny 1994). These and other meetings have resulted in certain sites being designated as "wetlands of international importance," "hemispheric reserves for shorebirds," or "conservation wetlands" (Thompson and Merritt 1988, Dugan 1990, Whigham and others 1993). Much of this effort has coincided with, and perhaps to some extent been fueled by, the environmental movement that began in the 1960s. Although this societal movement produced a groundswell of public, private, and scientific interest and involvement in environmental issues dealing with wetlands and wildlife, which persists even today, most efforts have turned out to be nothing more than "eco-speak"—words that convey good intentions, rally support from certain facets of society and polarize others, but have little or no mechanism for implementing real changes in environmental management policy. In point of fact, a virtual mountain of good intentions, scientific meetings, and proclamations pointing out the need to protect wetlands for wildlife conservation and other beneficial uses has done little to prevent their continued degradation. This has been particularly true when the opposing force was irrigated agriculture.

In this paper we illustrate the magnitude of the issue by presenting case examples that span four continents. In addition to focusing attention on the issue in a broad sense, it is critical to provide constructive guidance to those that seek to correct problems at a local level. To that end, we also discuss an economic-based approach for developing site-specific water policies that will address the needs of wetlands and wildlife.

Case Examples

North America

Background. Limited availability of water was one of the major obstacles to early settlement of many arid and semiarid regions in western North America (Reisner 1986). In the United States, the shortage of water and perceived need to homestead on desert lands led to the establishment of the US Bureau of Reclamation in 1902 (then named the Reclamation Service). The primary mission of this agency was to "reclaim" unproductive lands by bringing water to arid regions and turning desert into farmland. This reclamation began in earnest with the completion of the Newlands Water Project in Nevada in 1915 and reached a peak with the building of such massive water storage/diversion projects as Hoover Dam on the Colorado River, the California Aqueduct across the Mojave Desert, and the Central Valley Irrigation Project in California (Reisner 1986, Hoffman and others 1986). However, the price for this reclamation and the associated increase in agricultural production was a sharp decline in the amount of water available to native wetlands. For example, most of the historic flows of the upper and middle reaches of the San Joaquin River, California, are impounded and diverted for agricultural irrigation (Clifton and Gilliom 1989, State of California 1990). Native fishes and aquatic communities have disappeared and the once important runs of chinook salmon (*Oncorhynchus tshawytscha*) no longer take place (Moyle 1976, Moore and others 1990). About 90% of the historic wetlands in California's Central Valley are gone, due primarily to irrigated agriculture, and over 60% of the entire Pacific flyway waterfowl population is now channeled into the remaining wet-

Figure 1. A sample of significant wetlands in North America affected by irrigated agriculture. L marks the location of the Lahontan Valley wetlands, which include Stillwater Marsh, and the numbers identify the following wetlands: 1, Kesterson Marsh; 2, Grasslands Marshes; 3, Rasmus Lee Lake and Goose Lake wetlands; 4, Ouray wetlands; 5, Benton Lake wetlands; 6, Mexican riverine wetlands; 7, South Saskatchewan River Basin wetlands.

lands during migration (Frayer and others 1989). Catastrophic mortality has resulted because large numbers of birds are forced into small areas, where they are more susceptible to disease outbreaks brought on by crowding and contaminant-related stress (Gilmer and others 1982).

A combination of reduced freshwater inflows and contaminated subsurface irrigation drainage has seriously degraded wetlands throughout western North America (Figure 1, Table 1). Impacts to wildlife have been severe, and the conservation benefits provided by these wetlands have dropped precipitously (Lemly and others 1993, Lemly 1994a). Battles for water rights between settlers, agriculture, urban developers, and water authorities have raged for well over a century (Reisner 1986), but only in the last few years have the water needs of remnant native wetlands gained attention and become the focus of water management policy. A notable example is the wetlands located in the Lahontan Valley of northwestern Nevada (Figure 1). Consisting of Stillwater Marsh, Carson Lake Marsh, and the Carson Sink, these wetlands form the terminus of the Carson River. Their story provides an excellent illustration of the irrigation–wildlife dilemma in North America.

Conservation values of the Lahontan wetlands. The Lahontan Valley wetlands are of paramount importance in maintaining breeding populations of shorebirds, marshbirds, and waterfowl that are managed and protected under the North American Migratory Bird Treaty Act (Margolin 1979). These western Nevada wetlands have long been recognized as a critical area for migratory birds in the Pacific flyway. Lahontan Valley supports about half the Pacific flyway's entire population of canvasback ducks (*Aythya valisineria*), and up to 90% of the flyway's snow geese (*Chen hyperborea*) stop to use Stillwater and Carson Lake marshes in the fall. Over 65% of the tundra swans (*Olar columbianus*, a federally protected species) nest at these wetlands and over 7000 redhead ducklings (*Aythya americana*, a species given priority conservation status by the US Fish and Wildlife Service) are produced annually. Although crowded into less and less habitat (see the section below on effects on wildlife), large numbers of birds utilize these wetlands. Peak populations of 12,000 tundra swans, 25,000 canvasback ducks, 20,000 redhead ducks, 150 bald eagles (*Haliaeetus leucocephalus*, a federally listed endangered species), 30,000 American white pelicans (*Pelecanus erythrorhynchos*), and over 250,000 other waterfowl have been recorded in recent years. The numbers of shorebirds and marshbirds include thousands of black-necked stilts (*Himantopus mexicanus*), American avocets (*Recurvirostra americana*), long-billed dowichers (*Limnodromus scolopaceus*), white-faced ibis (*Plegadis chihi*), and egrets (*Casmerodius albus, Leucophoyx thula*). The Lahontan wetlands have been classified as a Hemispheric Reserve within the Western Hemisphere Shorebird Reserve Network by an international panel of scientists (Thompson and Merritt 1988).

Benefits to community. Archaeological research indicates that humans have occupied the Lahontan wetlands for at least 5000 years (Raven and Elston 1988, 1989, 1990). The wetlands provided Native Americans with abundant food resources such as seeds and tubers from cattail, alkali, and hardstem bulrush; fish; waterfowl and their eggs; and marsh mammals. Simpson (1876) wrote about the abundance of fish in the marshes: "the lake is filled with fish . . . the Indians have piles of fish lying about drying, principally chubs and mullet." Fish bones are commonly found in archaeological sites at the wetlands, suggesting that fish were a significant source of food for the local people (Greenspan 1988). Fish have provided community benefits more recently as well. The Lahontan cutthroat trout (*Onchorhynchus clarki henshawi*) were much sought

Table 1. Sample of wetlands in North America where wildlife conservation efforts have been affected by irrigated agriculture[a]

Wetland	Status[b]	Agricultural cause of impact	Period of impact	Effects on wetlands and wildlife	References
Stillwater Marsh	NWR, Ramsar site, hemispheric reserve for shorebirds	Water diversions for crop irrigation resulted in >90% reduction of inflows and produced contaminated subsurface drainage.	1915–present	Loss of 71% of wetlands; production of shorebirds cut by >60%; death and deformity of birds and fish due to contaminants in irrigation drainage; mortality of endangered species.	Hoffman and others (1990), Hallock and Hallock (1993), Lemly (1994a)
Kesterson Marsh	NWR	Contaminated subsurface irrigation drainage.	1978–1985	Death and deformity of thousands of waterfowl and shorebirds; all marshland (2,388 ha) drained and sediments excavated. No wetlands remain.	Zahm (1986), Hoffman and others (1986), Marshall (1985)
Grasslands Marshes	NWR, SWMA, 70% private ownership	Freshwater inflows replaced by contaminated irrigation drainage.	1950–present	Accumulation of drainwater contaminants in shorebirds to toxic levels for reproduction.	Ohlendorf and others (1987), Hothem and Welsh (1994)
Rasmus Lee Lake, Goose Lake Wetlands	SWMA	Contaminated subsurface irrigation drainage.	1986–present	Bioaccumulation of selenium to toxic levels; death and deformity of waterfowl and shorebirds.	Peterson and others (1988), See and others (1992a,b)
Ouray Wetlands	NWR SWMA	Contaminated subsurface irrigation drainage.	1960–present	Bioaccumulation of selenium to toxic levels; death and deformity of waterfowl, shorebirds, and fish; mortality of endangered species.	Stephens and others (1988, 1992), Waddell and Stanger (1992), Hamilton and others (1996)
Benton Lake Wetlands	NWR	Freshwater inflows replaced by contaminated irrigation drainage.	1970–present	Bioaccumulation of trace elements to toxic levels in waterfowl, shorebirds, and fish; reproductive impairment in birds.	Knapton and others (1987), Lambing and others (1987)
Mexican Riverine Wetlands	WP SWMA	Diversion of freshwater inflows for irrigation; salinization of surface and ground water supplies.	1963–present	Loss of >50% of wetlands and shallow water habitat; local loss of up to 68% of native fish species; total extinction of 15 rare or endangered fish species.	Contreras-Balderas and Lozano-Vilano (1994)
South Saskatchewan River Basin Wetlands	NP PP PWMA	Diversion of freshwater inflows for irrigation; salinization of surface and ground water supplies.	1940–present	Loss of >40% of wetlands and shallow water habitat; declines in bird usage and production.	Livingstone and Campbell (1992), Gilbert and Ramey (1995)

[a]Refer to Figure 1 for location of wetlands.

[b]NWR: national wildlife refuge; SWMA: state wildlife management area; WP: wildlife preserve; NP: national park; PP: provincial park; PWMA: provincial wildlife management area.

after by fishermen in the early 1900s. The sport fishery potential of the wetlands led to the introduction of several species of nonnative fishes between 1920 and 1940. Some adapted well and provided substantial recreational opportunities for local anglers. Largemouth bass (*Micropterus salmoides*), for example, supported a highly popular fishery until the 1970s, when the population virtually disappeared (see the section below on impacts of irrigation). Other current uses of the wetlands by local people include hunting, trapping, fishing, birdwatching, swimming, hiking, camping, and conservation education classes.

In addition to direct benefits to the local community, there are considerable benefits that extend far beyond the Lahontan Valley. For example, the Lahontan wetlands are an essential link in the support system for waterfowl that are sought by hunters throughout the Pacific flyway, which includes a huge area of the western United States, Canada, and Mexico. The economic revenues associated with waterfowl hunting can be substantial. In California, for example, these revenues exceeded US$85 million in 1990 and formed the livelihood of people ranging from hunting guides to industry workers that manufacture hunting equipment (Moore and others 1990). In addition to migratory waterfowl, many species of shorebirds (pelicans, curlews, stilts, avocets, etc.) that nest in Stillwater and Carson Lake marshes are enjoyed for nonconsumptive uses at locations far distant from the Lahontan Valley. In Arizona and New Mexico, for example, environmental education and conservation classes, nature trail tours and hikes, and birdwatching all involve wildlife that can be traced to western Nevada wetlands. The distant values and benefits associated with these wetlands were a key factor leading to the decision for their designation as a Hemispheric Reserve in the late 1970s (Thompson and Merritt 1988).

Impacts of irrigation and effects on wildlife. An extensive wetland ecosystem comprising some 70,000 ha existed in low areas of the Carson Desert of northwestern Nevada prior to completion of the Newlands Irrigation Project in 1915 (see Figure 1 for location). Of this amount, 14,000 ha in Stillwater Marsh, 11,000 ha in Carson Lake Marsh, and about 11,000 ha at the mouth of the Carson River in the Carson Sink (Fallon National Wildlife Refuge) were terminal drainage areas for the Carson River and were directly impacted by the Newlands Project. Since initiation of the project in 1905, the quantity and quality of the water reaching the terminal wetlands has declined precipitously. Water quantity has been reduced due to diversion of water from the Carson River for use in irrigating cropland, primarily to grow alfalfa that is harvested and sold as livestock feed in Nevada and neighboring states. Water quality has declined because of saline, contaminated subsurface drainage formed as a by-product of irrigation. The net effect has been elimination of 59,000 ha of wetlands in exchange for the water used to irrigate 22,000 ha of land. A summary of the changes that have occurred in water supplies, and associated wetland losses, is given in Tables 2 and 3. A total of 84% of the native wetlands are gone, and the remaining marshland receives water that contains up to 100 times the historic concentrations of dissolved solids, including toxic trace elements such as mercury, arsenic, and selenium (Hoffman and others 1990, Hallock and Hallock 1993). The changes in water quality have led to extensive declines in marsh vegetation in the remaining wetlands (Hoffman and others 1990, Lemly 1994a).

Irrigation-induced effects on wildlife have been severe. Fish populations are greatly reduced, and the species composition has changed since historical times. For example, Lahontan cutthroat trout, a federally listed endangered species, have been totally eliminated.

Table 2. Characteristics of water supply[a] for wetlands in northwestern Nevada, USA

Parameter and time period	Carson River	Carson Lake	Stillwater Marsh
Water quantity (ha-ft)			
Historical (1845–1960)	166,000	166,000	110,000
Recent (1970–1988)	121,000	10,000	22,000
Dissolved-solids concentration (mg/liter)			
Historical (1845–1960)	160	170	270
Recent (1970–1988)	220	1,170	1,170

[a]Data from Hallock and Hallock (1993).

Table 3. Wetland losses[a] in northwestern Nevada, USA

Location	Area (ha) Pre-1905	Area (ha) 1987	Loss (%)
Stillwater Wildlife Management Area	13,350	3,885	71
Carson Lake	10,925	2,265	79
Fallon National Wildlife Refuge	10,525	0	100
Winnemucca Lake National Wildlife Refuge	11,330	0	100
Humboldt Wildlife Management Area	23,475	5,260	78
Total	69,605	11,410	84

[a]Data from Hoffman and others (1990).

Largemouth bass, an introduced species that once supported an extensive recreational fishery, have also entirely disappeared. Most of the native species are now absent from the wetlands, and those that remain are pollution-tolerant fishes such as common carp (*Cyprinus carpio*) and mosquitofish (*Gambusia affinis*). The once diverse fish forage base supporting American white pelicans has been greatly reduced. River otter (*Lutra canadensis*), mink (*Mustela vison*), frogs, and turtles—characteristic marsh species that were once numerous—are all gone. Other species, such as the American curlew (*Numenius americanus*), have experienced precipitous declines in numbers, to the point that they are now uncommon. Muskrats (*Ondatra zibethicus*), freshwater clams, and aquatic snails were once abundant throughout the wetlands but only small, remnant populations remain. Freshwater clams, for example, are only present in Stillwater Point Reservoir, which is the area with the lowest concentration of dissolved solids (Hallock and Hallock 1993).

Waterfowl production is now much reduced compared to historical conditions. The numbers of nesting birds as well as the percentage of successful waterfowl and shorebird nests have steadily declined due to loss of wetland acreage and emergent vegetation coupled with exposure to contaminants in irrigation drainage water. Only about 25% of nests succeed in hatching even one chick, and the birds that do fledge contain elevated concentrations of mercury and selenium. Moreover, the water in many marsh areas is toxic to aquatic life because of the accumulated salts and trace elements that are leached out of crop land during irrigation and carried to the wetlands in drainwater (e.g., selenium, boron, molybdenum, lithium, arsenic). There are also public health concerns. Selenium, for example, accumulates in biota to concentrations that are 10,000 times those present in water, resulting in tissue residues in waterfowl that are four times the safe levels for human consumption (Hallock and Hallock 1993).

Water policy and outlook for the future. The trend of dwindling water supplies for Lahontan Valley wetlands, which began in 1905, continued unchecked until 1992. Degradation of Stillwater Marshes occurred throughout this period despite legislation (Migratory Bird Treaty Act in 1918), which supposedly provided for protection of aquatic bird habitat on national wildlife refuges (Vencil 1986). Diligent efforts were made by the US Fish and Wildlife Service (the principal agency responsible for managing the wetlands) to identify and characterize problems and propose solutions to the water issues affecting the Lahontan Valley wetlands beginning in the late 1970s (Thompson and Merritt 1988). These efforts achieved very limited success. Prior to 1987, the federal management agreements between the US Fish and Wildlife Service (FWS) and the US Bureau of Reclamation (USBR, the agency responsible for the Newlands Irrigation Project) did not protect water supplies to the wetlands, i.e., there were no specific water rights that would ensure the size or integrity of remaining wetlands. In principle, virtually all of the water flow of the Carson River was available for irrigation or other uses. The marshes obtained water after the needs of agriculture were met—through controlled releases from irrigation canals or as a result of surface and subsurface return flows from flood-irrigated land—and from precautionary flood-control releases (spills) from nearby Lahontan Reservoir. Thus, the wetlands were forced to exist entirely on leftovers, most of which were degraded in quality and not predictable, protected, or guaranteed. Recognizing the uncertainty of even these meager leavings, the FWS reached an agreement with the USBR in 1987 that established a limited water right to secure the available agricultural drainage and precautionary spill water for use in wetland management at Stillwater National Wildlife Refuge (Hoffman and others 1990).

Research studies conducted by the FWS in 1988–1990 further delineated the link between agricultural irrigation in the USBR's Newlands Project and toxic threats to wildlife on Stillwater Refuge (Hallock and Hallock 1993). Because the FWS has federal and international legal responsibilities for wildlife on the refuge, i.e., it is obligated to provide suitable (uncontaminated) habitat for birds that are managed and protected under the US–Canada–Mexico Migratory Bird Treaty Act, it brought a legal challenge against the USBR to obtain clean water supplies for maintaining permanent wetlands. A ruling and subsequent order issued by US Federal Court led to the establishment of operating criteria and procedures (OCAP) for the Newlands Project in 1992. Recent (1967–1986) average wetland sizes for Carson Lake and Stillwater Marsh were 4000 ha and 5600 ha, respectively. Under OCAP, the USBR is required to deliver sufficient water to maintain about 2000 ha of wetlands at Carson Lake and about 2800 ha at Stillwater, which reduces them to less than 10% of their historical size. Thus, although a yearly supply of water was mandated by law, the net effect was a loss of wetlands. Moreover, a mixture of irrigation drainage and freshwater can be supplied, which results in dissolved-solids concentrations four to seven times greater than historical conditions (Hallock and Hallock 1993).

Stillwater National Wildlife Refuge and the other remnant Lahontan Valley wetlands do not have a bright future. The legal challenge brought by the FWS had little effect on water policy. The court action amounted to settlement of an interagency argument without remedying the situation on the refuge. This case example illustrates the fact that agricultural interests can succeed in controlling water policy even if there are legal factors that would seem to favor wetlands and wildlife. OCAP will be the rule of law throughout the foreseeable future unless a substantial new challenge is mounted. It is possible that such a challenge could be successful if it combines the forces of wetland managers armed with a strong economic-based case for changing water policy, with well educated and involved local communities (see the section below on reversing the trend).

Australia

Background. Agricultural development is concentrated in the southeast and southwest and along the east coast of Australia (Newman and others 1996, Saunders and others 1996), where most of the population lives and rainfall is relatively high and reliable. Most of the continent is arid (about 70%) with highly variable rainfall (Stafford Smith and Morton 1990). Pastoralism (grazing) is the principal land use in arid regions, with livestock (sheep and cattle) dominating agricultural production. The tropical belt across northern Australia is also predominantly grazed by livestock and threats to many wetlands reflect this grazing (Blackman and others 1996, Whitehead and Chatto 1996).

The impact of agriculture on wetlands of Australia is significant (Goodrick 1970, Lane and McComb 1988, Lothian and Williams 1988, Norman and Corrick 1988, Pressey and Harris 1988). The most serious causes are draining of wetlands, diverting water from wetlands, and drowning of wetlands (Figure 2, Table 4). Generation of electricity (Kirkpatrick and Tyler 1988, Kingsford 1995) and urban development (Lane and McComb 1988, Adam 1995) have destroyed wetlands, but agriculture has caused most wetland loss. Coastal swamps were drained to graze livestock or plant sugar cane (Table 4). In the southeast corner of Western Australia, clearing and irrigation of land to grow cereals raised the water table and caused the salinity of wetlands to rise. The 1960s was the beginning of the great development of water resources within Australia. In New South Wales, for example, a 25-year plan was initiated in 1971 to spend A\$723 million (about US\$60 million, in 1997 dollars), primarily on building dams (WRIC 1971). Australia now boasts the largest per capita water storage in the world (Wasson and others 1996). In New South Wales there are 144 large storage reservoirs, each with a capacity of greater than 1000 Ml (10^6 liters) (Kingsford 1995). These have had a significant impact on wetlands and water resources in the country. Management of water for irrigation, mainly with large dams, has severely

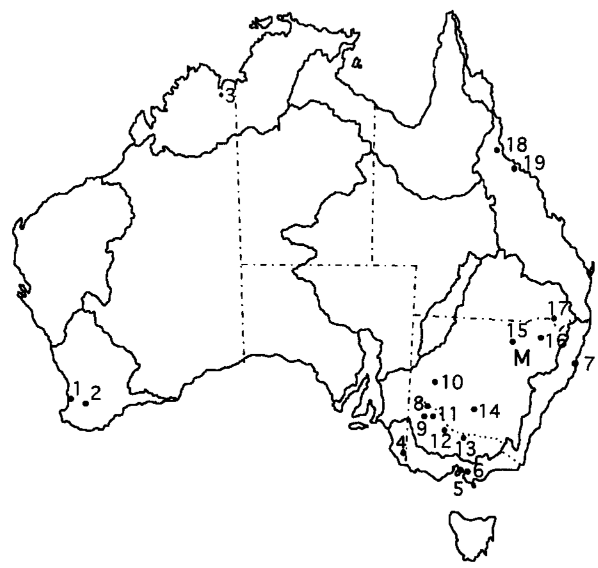

Figure 2. A sample of significant wetlands in Australia affected by irrigated agriculture. Lines mark the major drainage divisions in Australia. M marks the location of the Macquarie Marshes and the numbers refer to the following wetlands: 1, Swan Coastal Plain; 2, Lake Toolibin; 3, Ord and Parry River floodplains; 4, Bool Lagoon; 5, Carrum wetlands; 6, Koo-wee-rup Swamp; 7, Macleay River floodplain; 8, Murray River wetlands; 9, Lake Albacutya; 10, Menindee Lakes; 11, Hattah-Kulkyne Lakes; 12, Kerang wetlands; 13, Barmah-Millewa Forest; 14, Murrumbidgee wetlands; 15, Narran Lake; 16, Gwydir wetlands; 17, Wetlands of the Border Rivers; 18, Herbert River floodplain; 19, Bowling Green Bay wetlands.

affected river flows (Walker 1985, Barmuta and others 1992, Maheshwari and others 1995) and wetlands (Pressey and Middleton 1982) (Table 4). With the changed water regime, many wetlands now store water permanently, which has killed aquatic vegetation adapted to wet and dry cycles (Table 4). A more insidious problem is the impact of upstream diversion of water on the extent and duration of flooding (Table 4). A notable example is the Macquarie Marshes (Figure 2).

Conservation values of the Macquarie Marshes. The Macquarie Marshes form the extensive terminal wetland of the Macquarie River (Figure 2), which begins about 460 km to the southeast with a catchment of 73,000 km^2. A small amount of water can flow through to the Darling River. The marshes are one of six wetlands listed under the Ramsar Convention in the state of New South Wales (790,000 km^2) and were one of the first wetlands in Australia to be recognized for their conservation importance. Part was declared a bird and animal sanctuary at the beginning of this century (Paijmans 1981), culminating in the protection in 1971 of 18,000 ha under legislation as a nature reserve.

The Macquarie Marshes are best known as one of the

Table 4. Sample of 20 key wetlands in Australia affected by irrigated agriculture[a]

Wetland	Status	Agricultural cause of impact	Period of impact	Effects on wetlands and wildlife	References
Barmah/Millewa Forest	Ramsar site	Diversion and regulation of water for irrigation. Timber harvesting. Flows in the wetland regulated.	1936–present	About 50% of wetland lost. Decreased flood frequency and changes in season of flooding. Wetland vegetation less reliant on flooding replaced more aquatic vegetation.	Buckmaster and others (1979), Bren (1988, 1992)
Wetlands of the Border Rivers	No reserve status	Diversion and regulation of water for irrigation.	1980–present	Decreased wetland flooding.	Kingsford (unpublished)
Bowling Green Bay	National park, Ramsar site	Water augmentation to inflowing rivers from irrigation.	1970–present	Altered hydro-period drowns vegetation.	Blackman and others (1996)
Carrum swamplands	No reserve status	Swamps drained for agriculture.	1870–1950	Wetland area declined from 10,000 acres to 200 acres.	Norman and Corrick (1988)
East coast wetlands of New South Wales	Includes Kooragang Island nature reserve	Drainage schemes to limit flooding damage to agricultural and urban land.	1900–1980s	Drainage affected 96% of wetland area on Macleay River floodplain.	Goodrick (1970), Pressey (1989)
Gwydir wetlands	No reserve status	Diversion and regulation of water for irrigation. 70% reduction in floods of 100 Gl/month. Flooding frequency halved, from one in two years to one in four years. Drains and channelization. Elevated levels of herbicides and insectides (endosulfan) detected.	1960s–present	Reduction in areas of aquatic vegetation, reed beds from 4,000 ha to 250 ha. Abundance and diversity of waterbirds declined: 58 species to 45 species.	Debus (1989), Keyte (1992), Bennett and Green (1993)
Hattah-Kulkyne Lakes	National park, Ramsar site, biosphere reserve	River regulation has reduced inflows to the lakes from the Murray River.	1900–present	Increased blooms of cyanobacteria. Reduced flood frequency.	Hull (1996)
Herbert River floodplain	National park (part), wetland reserves, fish habitat reserve	Decline in water quality caused by sugar cane production. Drains replaced natural watercourses.	1960s–present	Most of wooded swamps and many other wetlands destroyed.	Blackman and others (1996)
Kerang wetlands	Ramsar site wildlife reserves	Water levels held permanently high in wetlands. Increased salinity. Levees to control flooding, channelling of water courses. Saline water disposed in some wetlands.	1936–present	Prolonged inundation caused loss of aquatic vegetation adapted to wet and dry cycles. Increased salinity affected fauna and flora.	Hull (1996)
Koo-wee-rup Swamp	No reserve status	Drainage for agriculture.	1960–1980	No wetland remains, declined from 40,000 ha. No aquatic plants or animals.	Norman and Corrick (1988)
Lake Albacutya	National park, Ramsar site, National Heritage	Historical records indicate reduced flooding because of upstream diversion of water for irrigation. Rising saline groundwater.	1920s–present	Degradation of vegetation communities.	Hull (1996)

Table 4. (Continued)

Wetland	Status	Agricultural cause of impact	Period of impact	Effects on wetlands and wildlife	References
Macquarie Marshes	Nature reserve, Register of National Estate, Ramsar site	Diversion of water upstream mainly for irrigation.	1969–present	Reduced wetland size by at least 40%–50%. Number of waterbirds and species in decline. Wetland vegetation in decline.	Kingsford and Thomas (1995)
Menindee Lakes	Included in Kinchega National Park	Water levels kept artificially high for irrigation and public water supply. Tandou Lake no longer a wetland.	1950s–present	Aquatic vegetation killed by too much flooding. Reduced numbers of waterbirds. Waterbird community dominated by piscivores. Erosion of lakeshores.	Kingsford (1995)
Murray River wetlands	No reserve status	Water levels kept artificially high for irrigation on 35% of wetlands.	1900–present	Death and deterioration of floodplain vegetation.	Bren (1990), Pressey (1990), Smith and Smith (1990)
Murrumbidgee River wetlands	No reserve status	Water levels kept artificially high; 62% of wetland area with water levels controlled locally.	1950s–present	570 ha of floodplain eucalypt trees killed; ducks did not breed where water levels were highly controlled. Breeding of herons, egrets, and cormorants dependent on flooding of red gum. Loss of some breeding habitat for egrets.	Briggs and others (1994), Thornton and Briggs (1994), Briggs and others (1997)
Narran Lake	Nature reserve	Water diversion for irrigation.	1985–present	Reductions of flow by 31%.	DPI (1996)
Ord and Parry River floodplains	Nature reserve and Ramsar site	Building of reservoir (Lakes Argyle and Kununurra). Reduced flooding. Ord irrigation scheme diverts water.	1972–present	Prevented migration of fish; impact on downstream wetlands. Submerged seasonal wetlands (e.g. Packsaddle Swamp).	Lane and McComb (1988)
Swan Coastal Plain	No reserve status	Drainage of wetlands for agriculture, roads, urban development. Increased water levels.	up to 1964	70% of wetlands lost or significantly altered by clearing of vegetation.	Halse (1989)
Southwest Western Australia	Affected nature reserves include Lakes Toolibin (Ramsar site); Dumbleyung, Coyrecup, Pinjarrega, Nonalling, Beverley lakes	Clearing of dryland vegetation for agriculture.	1900–1960s	Salinization of wetlands is common.	Halse (1987), Lane and McComb (1988), Froend and others (1987), Halse and others (1993)
Lower south east wetlands of South Australia (include Bool Lagoon)	Bool and Hacks Lagoon (Ramsar site; conservation park)	Drainage to increase availability of lands for grazing livestock.	1863–1981	Loss of wetlands; affected 53% of flood prone areas; more than 93% loss of permanent lakes and swamps.	NRC (1993), Jensen and others (1983)

[a]Refer to Figure 2 for location of wetlands.

more important sites in Australia for colonially breeding waterbirds (Marchant and Higgins 1990). During the 1990 flood, more than 80,000 nests were estimated in the Macquarie Marshes (Johnson personal communication); before extraction of water, colonies were numbered at more than 100,000 (Cooper 1954). In 1990, ciconiiformes were the most common colonially breeding waterbirds. Most were straw-necked ibis (*Threskiornis spinicollis;* 55,000) with glossy ibis (*Plegadis falcinellus;* 1000), Australian white ibis (*Threskiornis aethiopica;* 6700), intermediate egrets (*Ardea intermedia;* 17,000), and rufous night herons (*Nycticorax caledonicus;* 1500). Seventy-two species of waterbirds are recorded from the Macquarie Marshes, including 43 breeding species (see list in Kingsford and Thomas 1995). Seven of these are listed as threatened under legislation in New South Wales (e.g., magpie geese, *Anseranas semipalmata*) and 15 are covered by bilateral migratory bird agreements between Australia and Japan. The Macquarie Marshes have the largest stand of river red gums (*Eucalyptus camaldulensis*) in northern New South Wales, the largest reed beds of any wetland in New South Wales, and the most southerly occurrence of collibah woodland (*E. coolibah*) (EPA 1995).

The Macquarie Marshes also act as a filtering system. Water quality is generally improved as it flows through the Macquarie Marshes. The marshes filter total phosphorus, total nitrogen, and suspended solids when flows are sufficiently high (DWR 1994, DLWC 1995). There is also some evidence that the Macquarie Marshes are reducing rising salt loads in the Macquarie River by removing the salt and behaving as a groundwater recharge system (Williamson and others 1997).

Benefits to community. About 14% of the Macquarie Marshes is reserved under legislation (Kingsford and Thomas 1995), with the rest managed by private landholders under freehold or lease to the government of New South Wales. Most of these landholders graze cattle and have lived in the area since the beginning of the 20th century. The value of their holdings is dependent on flooding, which provides forage for cattle. Based on November 1996 estimates (regional gross margin), the value of grazing in the Macquarie Marshes is estimated to be A$5.2–7.5 million (about US$430,000–620,000) (Cunningham 1997). Of 27 landholders interviewed throughout the Maquarie Marshes, all believed that river regulation and extraction of water had disastrously affected the area (Cunningham 1997). As the wetland has contracted, so have their livelihoods. According to one landholder, whose family settled in the Marshes in the 1880s, his capacity to raise cattle has declined considerably because of water extraction upstream (McHugh 1996). Grazing may also have significant effects on wetlands (Robertson 1997).

Management of the Macquarie Marshes cannot be solely local. The reliance of other parts of Australia on the successful breeding of waterbirds in the Macquarie Marshes, the size of the wetland, and its international recognition mean that the wider Australian community has an input into its management. Tourism in the area is growing, despite the difficulty in accessing parts of the Macquarie Marshes. At least one landholder offers accommodation for visitors. The reserve does not have the status of a national park, so tourism is not encouraged. No facilities are available within the Macquarie Marshes Nature Reserve but open days once a year attract at least 100 people.

The Macquarie Marshes are an important part of the culture of Australian society. For the local rural communities, the wilderness of the Macquarie Marshes was regarded as a challenge for young men charged with rounding up cattle (McHugh 1996). On 9 April 1993, about 1000 people traveled to the Macquarie Marshes for a concert (McHugh 1996). The band Sirocco launched their tribute to the Macquarie Marshes (Wetland Suite: A Celebration of the Macquarie Marshes) by staging a concert that was broadcast by satellite by Radio Australia (Australian Broadcasting Corporation) to an estimated 50 million people.

Impacts of irrigation and effects on wildlife. In 1896, the first weir was built on the Macquarie River to manage water. Nine large dams, five major weirs and several minor weirs, a water transfer scheme, and numerous other regulatory structures (Kingsford and Thomas 1995) store water for later release to a large irrigation industry. About 89% of the water diverted from the Macquarie River is used for irrigation (DWR 1991). Irrigation increased after Burrendong Dam was built in 1967. Burrendong Dam has a storage capacity 70% larger than any other regulatory storage in the Macquarie Valley. Irrigated cotton was first grown in the Valley in 1967 (McHugh 1996) and now accounts for more than half of the water use for irrigation (DLWC unpublished data). It peaked in 1993–1994 when 543,000 Ml (10^6 liters) were diverted for irrigation. Originally flooding up to 1,280,000 ha (SKPPL 1984), the Macquarie Marshes now inundates about 130,000 ha during large floods (Kingsford and Thomas 1995).

The impact of irrigated agriculture on the wetland and its waterbirds is profound. The total amount of water reaching the Macquarie Marshes is a highly significant predictor of wetland size (Kingsford and Thomas 1995). Due to reduction in flows as a result of diversion of water upstream mainly for irrigated agriculture, the wetland is now conservatively 40%–50% smaller than it was before water was diverted (Kingsford and Thomas 1995). Before the Burrendong Dam was built, about 50% of the water that passed the upstream gauge at Dubbo reached the Macquarie Marshes. Now only about 21% of this water reaches the marshes, despite no changes in catchment rainfall in the period 1944–1993 (Kingsford and Thomas 1995). Areas of river red gums in the main area of the Macquarie Marshes have declined by about 14% (Brereton 1994) but may have declined by significantly more on the margins of the marshes. Red gums in one area declined by over 50% between 1934 and 1981; reed beds experienced similar declines between 1963 and 1972 (Brander 1987). Water couch (*Paspalum paspaloides*) has declined by 40% in some areas during the period 1949–1991, with exotic dryland vegetation replacing it (Brereton 1994). Numbers of waterbirds and the numbers of species declined in the period 1983–1995 (Kingsford and Thomas 1995, Kingsford unpublished data). Reduced flows have also impacted the size of breeding colonies of ciconiiformes (Kingsford and Johnson unpublished data). Conservatively, this has probably meant that there are now about 100,000 fewer nests over a period of 11 years as result of water that was diverted from the Macquarie River (Kingsford and Johnson unpublished data). Fish surveys also indicate a decline (WRC 1979).

A smaller scale impact is that of water levels that are maintained higher than normal in some stream channels to supply irrigation and livestock needs. These artificial levels have killed aquatic vegetation adapted to seasonal drying in parts of the marshes. Some channels have eroded, limiting the potential for flows to go over their banks and inundate the floodplain (EPA 1995).

As well as impacts of irrigation upstream of the Macquarie Marshes, about 11,000 ha of the Macquarie Marshes were landscaped for irrigation, with about another 4400 ha potentially irrigated during floods or high flows (McHugh 1996). In 1991 cotton was grown on the floodplain of the Macquarie Marshes, adjacent to the nature reserve (McHugh 1996).

Irrigation upstream of the Macquarie Marshes is also raising water tables, which has caused salinity problems that are contributing to long-term increases in the salinity of water reaching the Macquarie Marshes (Williamson and others 1997). Four pesticide products occur in the river: endosulfan, atrazine, prometryn, and parathion (O'Brien 1995). Most sampling during the summer of 1994–1995 at two sites at the beginning of the Macquarie Marshes detected levels of endosulfan greater than 0.01 μg/l, which is the agreed threshold for protection of aquatic ecosystems (O'Brien 1995).

Water management plan and outlook for the future. Revision of the 1986 Water Management Plan for the Macquarie Marshes (DWR and NPWS 1986) began in March 1994. The name of this policy instrument belies its importance; it deals with water management in the entire Macquarie Valley. The 1986 plan did not prevent a rapid increase in diversions of water upstream of the Macquarie Marshes. There were 200 submissions to an issues paper and 1600 submissions to a draft revised plan in 1995. The Macquarie Marshes Water Management Plan was published in August 1996 (DLWC and NPWS 1996) and aimed ". . . to identify and secure flows, from a finite water resource shared with others, to ensure the ecological sustainability of the Macquarie Marshes" (DLWC and NPWS 1996). There were eleven rules about access to water. The main ones were an increased allocation of water to the Macquarie Marshes of 75,000 Ml—in addition to 50,000 Ml that was already provided—and a limit on access to uncontrolled tributary flows or dam spills of 50,000 Ml. For this process, uncontrolled flows from downstream tributaries or dam spills are declared surplus and are accessible for the irrigation industry, which can pump water into large off-river impoundments. During one year in the early 1990s about 200,000 Ml of this uncontrolled flow was diverted.

The effect of the rules for managing flows to the Macquarie Marshes is estimated to reduce by 14% average diversions to irrigation, resulting in a long-term average impact of 6% on gross economic margins in the Macquarie Valley (DLWC and NPWS 1996). However, the prediction of a 6% economic loss did not include the positive economic benefits such as livestock grazing. Importantly, the plan established management principles for the sustainability of the Macquarie Marshes in clear recognition of the long-term impact of diversions upstream. Although criticized by the irrigation community, the plan received some local support. Of 112 riparian landholders between the southern end of the marshes and the Barwon River, mainly graziers, 109 (97%) supported the initiative to restore flows to the Macquarie Marshes through the policy changes put forward in the Macquarie Marshes Water Management Plan. In contrast, the reception by the irrigation industry upstream of the marshes was hostile. The rural town of Trangie was closed down as 1200 of the rural community demonstrated against the policy. A group set up to advise on water management in the Macquarie River, the Macquarie River Advisory Council, prepared an alternate plan after engaging a wetland ecologist. In late 1995, nine of the 12 members on the council represented irrigators or had irrigation interests, and there were no environmental representatives (Media

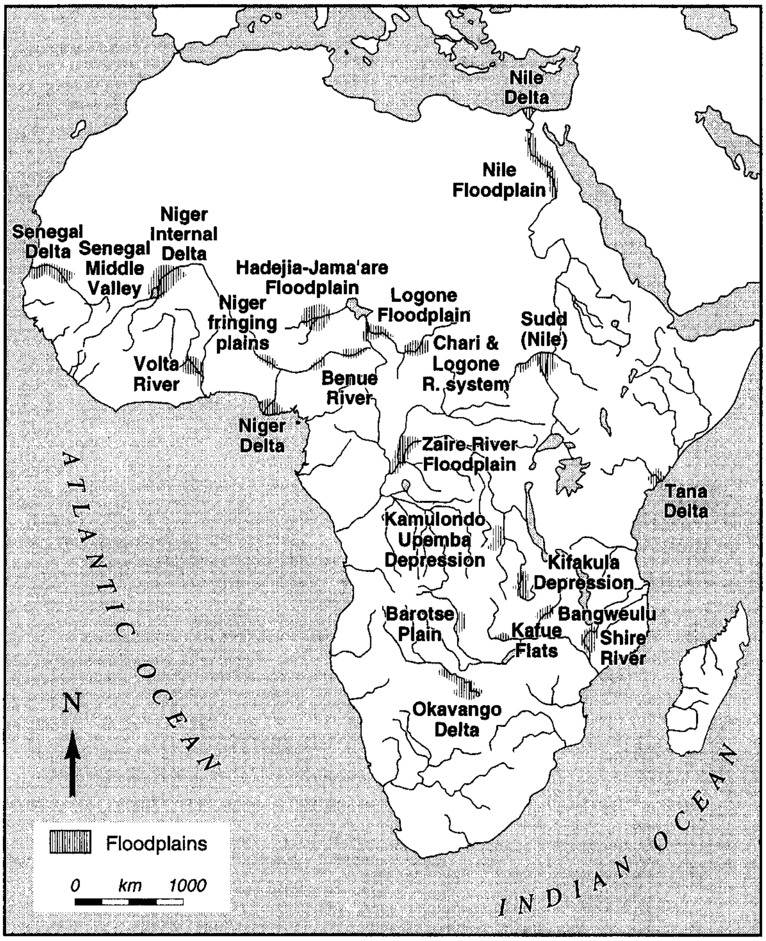

Figure 3. Major African floodplain wetlands.

Associates 1997). Some of the proposals put forward by the council were incorporated in the final Macquarie Marshes Water Management Plan, but insufficient scientific evidence was given to support their full alternate plan. Its focus was management of water within the Macquarie Marshes, ostensibly avoiding the issue of increasing diversions upstream. The 1996 plan established a much broader advisory group of 12 community members, only one of whom directly represented irrigation interests.

The policy as set out in the Macquarie Marshes Water Management Plan (DLWC and NPWS 1996) represents a landmark in the sustainable management of water resources in Australia. Nowhere else has the difficult problem of ecological sustainability of wetlands and the impact of irrigated agriculture and its diversion of water upstream been seriously grappled with at a catchment level. Moreover, of all the examples given in this paper, the Macquarie Marshes are the only wetlands where degradation has been effectively halted. Conditions have stabilized primarily because of very strict controls on access to irrigation water. Importantly, there is a commitment to evaluate the availability and allocation of water within the catchment as a whole rather than focusing on isolated or segmented areas. The key to successful protection of these wetlands depended on closing the loopholes that so often exist in water management—loopholes that give agriculture first priority for water. At Macquarie Marshes, the loopholes were effectively closed by developing a plan for integrated management of the entire watershed, including the water needs for sustaining wildlife resources.

Africa

Background. The most extensive wetlands in the African continent are the large seasonally inundated floodplains (Figure 3). These wetlands, which include notable examples such as the Inner Delta of the Niger in Mali, the Sudd of the Sudanian Upper Nile and Zambia's Kafue Flats, provide valuable habitats for wildlife. They support a huge variety of birdlife and are vital for many migratory species that winter within them (Hollis 1986, Tréca and Ndiaye 1996). The presence of water in many floodplains during the dry season pro-

Table 5. Examples of impact of agriculture on Africa's floodplain wetlands[a]

Wetland	Status	Agricultural cause of impact	Period of impact	Effects on wetland and wildlife	References
Logone floodplain, Cameroon	Includes the Waza National Park	Upstream barrage for irrigation and riverside embankment to protect irrigation scheme.	1970–present	Reduced wet season inundation and loss of grazing for wildlife including ungulates and elephant.	Drijver and Marchand (1985), Wesseling and others (1996)
Floodplain of the Benue River, Cameroon	Close proximity to three national parks	Large dam and reservoir for 29,000 ha of irrigation.	1982–present	Loss of important wildlife habitat beneath the reservoir, reduction in downstream inundation, disruption of migration routes of large mammals including buffalo, antelope and elephant.	Drijver and Marchand (1985)
Hadejia-Nguru Wetlands, northeast Nigeria	Partly national park and nature reserves	Two large dams, one barrage and two large-scale irrigation schemes upstream. Expansion of small-scale irrigation within the wetlands.	1971–present	Reduced wet season inundation leading to declines in wildlife habitat. Removal of natural vegetation cover. Reports of river pollution with agricultural chemicals.	Hollis and others (1993a), Thompson and Hollis (1995), Thompson (1995), this paper
Phongolo floodplain, South Africa	Includes the Ndmu game reserve	Dam constructed upstream for 40,000 ha of irrigated land.	1970–early 1990s	Changes to hydrological regime of the floodplain including reduced flood flows and inundation extent. Recently an artificial flood regime has been established.	Acreman (1994), Bruwer and others (1996)
Senegal Delta, Senegal	Includes the Djoudj National Park, a Ramsar site, World Heritage site and national park	Upstream dam for irrigation and hydro-power, downstream barrage to prevent saline intrusion, river embankments to prevent flooding, expansion of irrigated agriculture.	1985–present	Loss of wetland habitat to numerous rice schemes. Reduced water supplies to some wetland areas, reduced fish populations, Encroachment of freshwater vegetation into areas of open water.	Drijver and Marchand (1985), N'diaye (1997), Vinke (1996)

[a]Refer to Figure 3 for location of wetlands.

vides important grazing areas for wild ungulates during periods when the surrounding drylands are desiccated.

In addition to their importance for wildlife, Africa's floodplains play a vital life-support role for a significant proportion of the continent's population (e.g., Drijver and Marchand 1985). Human populations have for centuries utilized the agricultural, fisheries, hunting, grazing, and water resources provided by floodplains (e.g., Adams 1996). These wetlands have rightly been termed "the heart of Sahelian life systems" (Drijver and Rodenburg 1988, Drijver and Van Wetten 1992).

Historically, the different uses of floodplain resources were integrated economically and ecologically (Adams 1992, Hollis and Acreman 1994). Floodplains have been able to support wildlife and people. However, the last 40 years have witnessed the development of many large-scale water management schemes, frequently associated with dams and irrigated agriculture (Thompson 1996). In 1987, Van Ketel and others identified 114 dams that were likely to impact wetlands in West Africa alone. Drijver and Van Wetten (1992) stated that by the year 2020 all Sahelian wetlands will be subject to the impacts associated with upstream dams. These impacts will have profound consequences for the wildlife and human populations that depend on these wetlands. Table 5 provides examples of African floodplain wetlands that, despite some degree of conservation status, have been detrimentally affected by agricul-

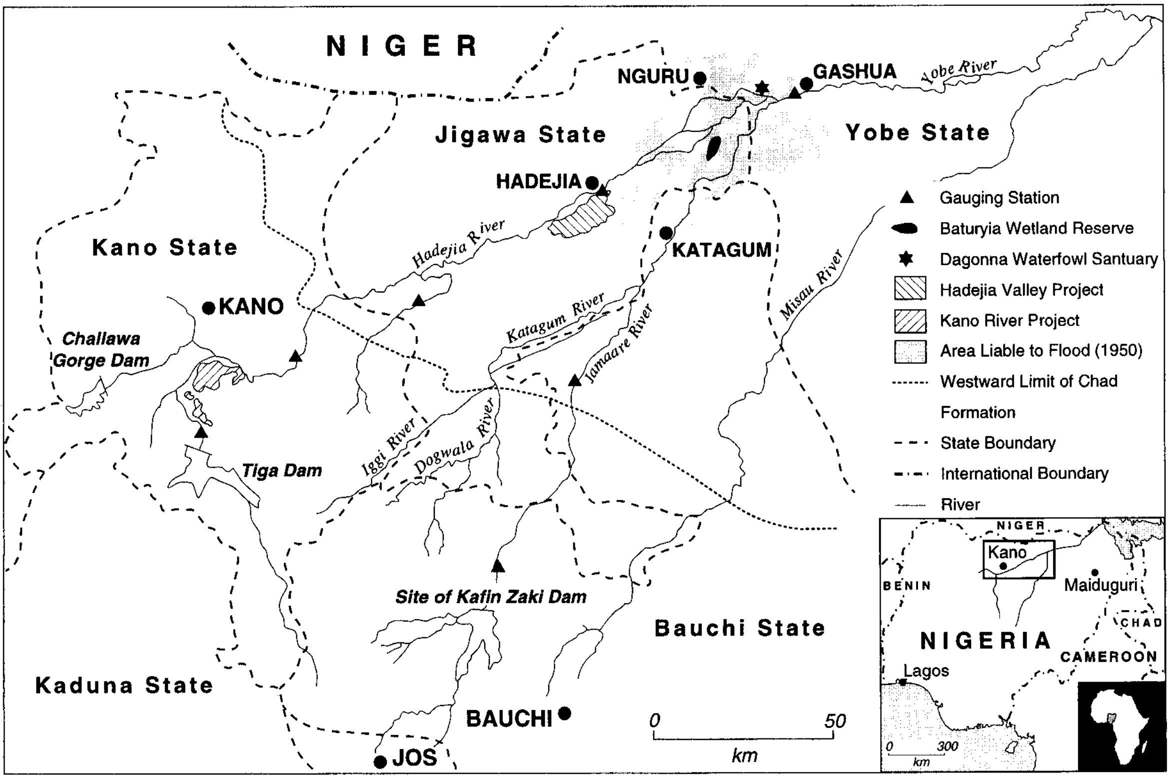

Figure 4. The Hadejia-Jama'are River Basin and the Hadejia-Nguru Wetlands.

tural activities. The floodplain wetlands of the Hadejia-Jama'are River Basin are a good example, with all the elements that characterize the conflict between agriculture, conservation, and sustainable wetland management in Africa.

Conservation values of the floodplain wetlands of the Hadejia-Jama'are Basin. The largest floodplain wetlands within the semiarid Hadejia-Jama'are Basin are located around the confluence of the Hadejia and Jama'are rivers (Figure 4). This area is commonly referred to as the Hadejia-Nguru Wetlands (e.g., Hollis and others 1993a). The wetlands are dependent upon wet season discharges originating in the wetter headwaters of these two rivers. For much of the year the basin's rivers are largely dry, and it is not until the beginning of the wet season in April or May that water begins to flow within their channels. Approximately 80% of the annual runoff upstream of the wetlands occurs during August and September (Hollis and others 1993b). As discharges increase, floodwaters begin to inundate the wetland's *fadamas* (the Hausa term for seasonally flooded areas). Peak flood extents, which historically often exceeded 2000 km^2, are attained during September–October (Thompson 1995). Subsequently, a gradual decline in flooding occurs so that by April only a few core areas remain inundated. These cover less than 10% of the peak wet season flood extent (Polet and Thompson 1996).

Vegetation communities within the wetlands reflect the governing influence of the wet season floods. The surrounding areas that are not inundated are characteristically scrub and bushland dominated by *Ziziphis jujuba, Acacia seyal,* and *A. arabica.* Grassland dominated by *Andropogon gayanus* and *Oryza bathii* borders the flooded zone, while semipermanent lakes and swamps are dominated by mats of floating *Echinochloa stagnina* (Adams and others 1993a).

The floodplains of the Hadejia-Jama'are Basin are exceptional for the support they provide to wildlife and human communities. Although Shelton (1984) reports that parts of the wetlands provide habitat for reedbuck (*Redunca arundium*), grey duiker (*Sylvicapra grimmia*), red-fronted gazelle (*Gazella rufifrons*), warthog (*Phacochoerus aethiopicus*), and bush pig (*Potamochoerus porcus*), it is for their waterfowl populations that they are famous. Annual bird surveys have identified over 70 different waterbird species from 15 families (Garba Boyi and Polet 1996a, Polet and others 1997). In 1997 the wetlands hosted over 320,000 water-related birds, many of which were Palearctic migrants. The importance of the wetlands for migratory birds has been emphasized by a number of workers. Perennou (1991) stated that they qualified as internationally important using Ramsar criteria. More than 1% of the western Palearctic populations of ferruginous duck (*Aythya nyoca*) have been counted in the wetlands, while they play host to over 2% of the total West African populations of white-faced tree duck (*Dendrocygna viduata*), spur-winged geese (*Plectropterus gambensis*), and knob-billed geese (*Sarkidiornis melanotos*) (Garba Boyi and Polet 1996b). Garba Boyi and others (1992) concluded that the Hadejia-Nguru Wetlands are the fifth most important site for Palearctic migrants in West Africa. Scott and Rose (1996) identified the wetlands as a key site for Anatidae (swans, geese, and ducks) in Africa and western Eurasia.

The wetlands' importance for wildlife is recognized through a number of conservation oriented designations. A central area of 938 km^2 forms one of three sites that constitute the Chad Basin National Park (Mamza 1995). Within the park hunting, fishing, grazing, agriculture, and other forms of disturbance are prohibited (Adams 1993). A number of smaller designated reserves also exist within the wetlands, most notably the Dagonna Waterfowl Sanctuary in the northeast and the Baturia Wetlands Reserve in the west-central part of the wetlands. Nigeria is at present not a signatory to the Ramsar Convention. However, the Hadejia-Nguru Wetlands would be a likely candidate for one of the country's first Ramsar sites if Nigeria embraces the convention in the future (Akinsola and others 1996).

Benefits to community. The Hadejia-Nguru Wetlands provide multiple benefits for human communities. The agricultural sector includes the cultivation of flood rice, recession and rainfed cropping, and small-scale irrigation based on surface and groundwater extraction (Polet and Thompson 1996). The wetlands are also an important center of fish production, while the floodplain forests provide fuelwood and timber. Barbier and others (1991) showed that these three sectors have a combined value of US$51/ha or, when related to the water required to inundate the floodplain, US$14,548/ha. The floodplain also provides important dry season pastures and numerous uses are made of wetland vegetation for both livestock and humans. The annual floods recharge the wetlands' shallow alluvial aquifers, which are the principal sources of potable water for over 1.5 million people.

Impacts of irrigation and effects on wildlife. Over the last few decades significant changes have taken place within the Hadejia-Jama'are Basin that have impacted both the wildlife and human populations within its floodplain wetlands. Drought has been a recurring influence that has reduced river flows and consequently the extent of inundation within the wetlands. A hydrological model of the basin (Hollis and Thompson 1993a, Thompson and Hollis 1995) shows that while flood extents exceeded 2000 km^2 in the 1960s, during the following decade the area inundated was commonly 1000–2000 km^2. Throughout the 1980s flood extents were even smaller; in 1984 only 300 km^2 flooded. Some relatively wet years have recently enabled flood extents to approximate those experienced in the 1970s. Superimposed on these natural variations are a number of human influences that have impacted the wetlands. The driving force behind these changes has been irrigated agriculture.

Within the wetlands the expansion of small-scale irrigation has led to the replacement of natural vegetation or rainfed agricultural land with small (typically 1- to 4-ha) plots in which relatively high-value crops such as wheat, peppers, onions, sweet potato, and tomatoes are grown. The expansion of this form of agriculture was aided by a sharp rise in wheat prices in the 1970s and 1980s resulting from a ban on wheat imports (Kimmage 1991). This coincided with the dissemination of approximately 70,000 portable irrigation pumps by the Kano State Agricultural and Rural Development Programme (KNARDA). This change in agricultural practices has enabled the cropping of areas previously considered marginal for cultivation (Akinsola and others 1996). It has led to the removal of habitat for wildlife, although at present no detailed estimates of the magnitude of this loss have been attempted. Muslim and Umar (1995) suggested that agricultural intensification has also resulted in increasing concentrations of chemical pollutants, largely from fertilizers, within the wetland's rivers.

A far more widespread impact on the wetlands has resulted from the construction of large-scale irrigation schemes and associated dams. There are currently over 20 dams within the river basin, all upstream of the Hadejia-Nguru Wetlands. The largest are associated with two major irrigation schemes located on the Hadejia River or its tributaries (Figure 4). The Kano River Irrigation Project (KRIP) is the biggest scheme at present. Irrigation water is provided by Tiga Dam, the largest dam in the basin, which was constructed during the period 1971–1974. The plan for KRIP envisaged its development in two distinct phases. A total irrigated area of 27,000 ha was planned for phase I (KRIP-I), while phase II (KRIP-II) would add a further 40,000 ha. Construction of phase I began in 1977, and to date around 14,000 ha have been completed. The main crops grown during the wet season are rice, maize, cowpeas, and millet, while in the dry season tomatoes and wheat predominate (Adams and others 1993b).

Plans to expand the scheme do exist, although FAO (1993) has highlighted the prerequisite for improved maintenance and rehabilitation of existing sections of the scheme.

The first phase of the Hadejia Valley Project (HVP), the second major irrigation scheme, is under construction. The scheme involves a barrage across the Hadejia River just upstream of the Hadejia-Nguru Wetlands and a planned 12,500 ha of formal irrigation. At present around 7000–8000 ha have been completed. Challawa Gorge Dam on the Challawa River, upstream of Kano, is linked to the HVP. The dam, which was completed in 1992, is designed to store water during the wet season and subsequently release it downstream for use on the HVP.

The development of these large-scale schemes has had a tremendous impact on the hydrology of the river basin. These impacts have been concentrated in downstream areas. By retaining and utilizing water upstream, the schemes have reduced the magnitudes of downstream flood discharges and thereby the area inundated within the floodplain. The first impacts were felt soon after the closure and filling of Tiga Dam in 1976. Reduced flood extents resulted in crop failures and declining fisheries within the wetlands. Stock (1978) suggested that the impacts of Tiga Dam were more severe than those associated with the droughts of the early 1970s. The declining flood extents are confirmed by the reported loss of recession farms along the Hadejia River (Wallace 1980). In 1977 local people were complaining that "the land is dying" (Kulatunga and others 1977, cited in Olofin 1996). Hydrological modeling undertaken by Hollis and Thompson (1993b) and Thompson (1995) shows that Tiga Dam and the KRIP have reduced peak flood extents by an average of 11%. These reductions are much more pronounced in dry years when ecosystems are already stressed. In 1984, for example, only 55% of the area that would have been flooded without the dam and irrigation scheme was actually inundated (Thompson 1995).

Declining flood extents have recently been compounded by the completion of the Challawa Gorge Dam and work on the Hadejia Valley Project. For example, dramatic declines in the inundated area were reported in 1992, the year in which the Challawa Gorge Dam came into operation. The hydrological model shows that flood extents are, on average, over 17% lower with the current extent of irrigation on the KRIP and HVP than those that could be anticipated if the schemes were not in place (Thompson 1995).

The negative impacts of declining flood extents upon human activities within the wetlands have been widely reported (e.g., Hollis and others 1993a). Wildlife can be expected to have been similarly affected. For example, the Baturia Wetland Reserve lies along the Keffin Hausa River, a major tributary of the Hadejia River. Historically the reserve was extensively inundated in the wet season. However, in recent years the area has been largely dry as flows within the Keffin Hausa have been reduced by drought, upstream irrigation schemes, and sedimentation within its channel. Groundwater levels in the area appear to have declined because the recharge provided by the floods has been lost. Consequentially the reserve's groundwater woodland is becoming degraded (Adams 1993). This process has been exacerbated by the illegal large-scale cutting of fuelwood in the area. The future of the reserve is uncertain.

Thomas and others (1993) predicted that since floodplain fisheries are closely related to flood extent (e.g. Welcomme 1985), the upstream irrigation schemes will have serious impacts on fish communities. This, in turn, has significant implications for the fauna dependent upon fish. It is a second blow to the waterfowl of the wetlands whose available habitat has been reduced by the declining inundation. Polet and others (1997) identified a close relationship between flood extent and numbers of water-related birds. Garba Boyi and Polet (1996a) found that both the number and species diversity of waterbirds were diminished in recent years of poor flooding. In particular, Akinsola and others (1996) highlighted the declining populations of large birds such as cranes, storks, and pelicans, which they attributed to declining flood extents. The remaining birds are congregating in the few remnant core areas that are flooded on a regular basis (Olofin 1996). The competition between wildlife and human activities such as agriculture and fishing is increasing in these areas. This conflict is exacerbated by a growing human population within the wetlands and the expansion of small-scale irrigation. Additionally, the concentration of birds in a few areas favors illegal hunting, which is a serious problem within the wetlands (Akinsola 1996). Any further expansion in the area of large-scale irrigation within the basin will clearly have tremendous implications for wildlife and human communities within the wetlands. In particular, plans for 84,000 ha of irrigation and a massive dam at Kafin Zaki on the as yet undammed Jama'are River will reduce flood extents by an average of over 50% (Thompson 1995).

Water policy and outlook for the future. The clear conclusion from this case study is that any form of conservation initiative for the wetlands must encompass activities taking place within the whole river basin. The major impacts on the floodplains of the Hadejia-Jama'are Basin have come from irrigation schemes several 100 km upstream. The example of the Baturia Wetland Reserve indicates that bestowing a protected status on an area does not prevent damage resulting from activities beyond the boundaries of the protected area. Within the Hadejia-Jama'are Basin considerable progress has been made towards the development of an integrated system for the allocation of water among the different parts of the basin (Polet and Thompson 1996). A water management plan is currently being prepared that will incorporate the water requirements of the wetlands as well as those associated with agriculture, domestic supplies, and industry. The plan will include the release of artificial floods from upstream dams in order to maintain inundation within the floodplain (Thompson and Hollis 1995). Much of the credit for these promising developments lies with the Hadejia-Nguru Wetlands Conservation Project, an IUCN field project based within the wetlands.

Central Asia

Synopsis of the Aral Sea episode. Spanning the borders of three former Soviet republics (Kazakhstan, Uzbekistan, and Turkmenistan), the Aral Sea was once the world's fourth largest terminal lake (area 68,000 km^2, volume 1090 km^3). It is being desiccated due to water diversions for agricultural irrigation. During the 1950s and 1960s, plans were developed for major expansion of irrigation in the Aral Sea Basin. At that time, it was predicted that the increased water demands would reduce inflow to the Aral Sea and reduce its size. However, using a typical agricultural cost–benefit scenario, most state authorities, and some scientists, viewed this as a worthwhile trade-off—river water would be far more valuable if used for irrigation than if allowed to reach the sea. This ecologically short-sighted, oversimplified scenario compared anticipated economic gains from irrigated agriculture with tangible (existing) benefits from the sea. Not surprisingly, the expected benefits from agriculture won out. Given the positive economic projections, many viewed the inevitable shrinkage of the Aral Sea to a brine lake as being desirable. The possibility of significant adverse environmental impacts was largely dismissed—the saving graces of irrigation were supposed to far outweigh any minor effects that might occur.

Large-scale irrigation quickly changed the Aral Sea ecosystem. Between 1960 and 1987, the surface elevation of the Aral dropped by almost 13 m, and its area decreased by 40% (Micklin 1988). If current water demands for irrigation continue unchecked, the Aral Sea will shrink to a salt-brine remnant that is unfit for human, agricultural, or wildlife use early in the next century. Although relatively unpublicized and unknown in the Western Hemisphere compared to the previous case examples from North American and Australia, the scale of impacts to the Aral Sea—on such a large body of water in such a short period of time—is unprecedented. The result ranks as arguably one of the world's most notorious environmental catastrophes, surpassing the nuclear contamination at Chernobyl and the petroleum spill of the *Exxon Valdez*. Russian commentators have referred to the situation as an impending disaster and one of the greatest ecological problems of the 20th century.

Some of the severe environmental problems that have occurred in the Aral Sea episode include: (1) Exposure of salt crusts—when the sea shrank, salts accumulated on the bottom and exposed some 27,000 km^2 of salt-encrusted beaches. Once dried, this crumbling salt is blown for distances up to 1000 km in massive salt-dust storms. Twenty-nine of these storms occurred between 1975 and 1981 alone. An estimated 43 million metric tons of salt are deposited annually as aerosols by rain and dew over a 200,000 km^2 area. Numerous wetlands and plant communities far distant from the Aral Sea have been heavily impacted because of this airborne salinization. (2) Loss of fish species—biological productivity has steeply declined due to salinization of the water. By the early 1980s, 20 of 24 native fish species had disappeared, and the commercial catch (48,000 metric tons in 1957) fell to near zero. Some fish canneries on the shores of the Aral Sea have closed (some fishing villages now lie 80 km from the shoreline); others slashed their work forces and persist only because of fish imported at high-cost from the Atlantic, Pacific, and Arctic oceans. Contaminated irrigation drainage (pesticides and herbicides) has polluted the water and fishery in several locations, prompting a halt to commercial fishing. Employment related to the Aral fishery, reported at 60,000 in the 1950s, has disappeared, leading to abandonment of many fishing villages. (3) Impacts on human health (UNEP 1992, Perera 1993, Pearce 1995)—in Karakalpakstan, a semiindependent republic of Uzbekistan: (a) 97% of 700,000 women are anemic (more than five times the number a decade ago); (b) there is a rising incidence of kidney and thyroid disease and of esophageal, stomach, and liver cancer in women; (c) the incidence of viral hepatitis has risen by 50% over last 10 years; (d) one in five men is rejected as medically unfit for military service; (e) life expectancy is 20 years less than average for rest of the former Soviet Union; (f) infant mortality is 50% above average for Uzbekistan and highest in the former Soviet Union (similar data are emerging for other areas close to Aral Sea); (g) the Uzbekistan government reports that 90% of irrigated fields in

Karakalpakstan are salinated, one in five has been abandoned, and 80% of fields in Kzyl Orda are affected by salt; and (h) the United Nations estimates that 75 million tonnes of salt, chemicals, and dust enter the atmosphere from the seabed during dust storms each winter. (4) Loss of wetlands and wildlife—the extensive delta wetlands that once existed at the mouth of the Syr Dar'ya and Amu Dar'ya rivers disappeared, along with the important ecological functions and societal benefits they provided, i.e., vast marsh grass acreage that formed a natural feed base for livestock, spawning grounds that supported commercial fishing, commercial hunting and trapping, abundant reeds that were harvested for industry, and irreplaceable habitat for wildlife conservation. Native plant communities in the remnant wetlands have degraded and, in some locations, completely disappeared. Much of the animal fauna that utilized the preirrigation wetlands is gone, for example, muskrat (*Ondatra zibethica*), wild boar (*Sus scrofa*), deer (*Cervus* sp.), golden jackal (*Canis aureus*); numerous birds, for example, ibis (*Platalea leucorodia*), pelican (*Pelecanus crispus*), swan (*Cygnus olor*), and flamingo (*Phoenicopterus ruber*); and several endangered species such as the Asian tiger (*Panthera tigris*). By the 1980s only 38 (20%) of the 173 animal species that once lived in the Aral wetlands survived (Micklin 1988).

The future of the Aral Sea and its remnant wildlife populations is uncertain at best. Reversing the sea's recession and many of the associated environmental problems could be achieved if more freshwater reached it. However, the water supplies are now ingrained into a new agricultural economic base—created and justified on false assumptions—that makes this possibility remote.

There may be ways to partially restore the sea with existing water supplies. By 1990 the sea's progressive fall in surface level divided it into two sections; a small northern part (Small Aral) and a much larger and deeper southern part (Large Aral). In 1992 an earthen dam was built to contain flows in the Small Aral as an attempt to stabilize the ecosystem within this small portion of the sea (Aladin and others 1995). Results were dramatic. Within nine months, the surface level rose by more than a meter and salinity began to decrease. Containing the inflow of freshwater significantly enlarged the brackish water zone of the Syrdar'ya River estuary and enabled freshwater fish to leave the Small Aral and feed in areas not occupied for 10–15 years. Invertebrates (amphipods and mysids), reeds, wading birds, and ducks returned to the estuary and restoration of some of the former biological diversity was evident. However, the dam broke in only nine months and these ecological improvements were quickly lost. In light of the 1992 experiment there has been considerable support for rebuilding the dam to make it a permanent part of the Aral Sea's long-term management strategy (Aladin and others 1995). Although conditions in the Large Aral would continue largely unchanged, the positive ecological benefits, combined with the fact that most of the human population and economic base resides along the coast of the Small Aral, makes this a favored option.

Preservation of the entire Aral Sea ecosystem would likely require implementation of a controversial project to divert water from western Siberia into the Aral Sea Basin. However, this proposal is meeting with strong opposition from those that would have to give up claim to their water. Having seen the disaster caused by water shortages at the Aral, sharing is difficult even among nations with close cultural and economic ties. The only positive action taken thus far has been construction of a collector canal to transport contaminated irrigation drainage from the Amu Dar'ya basin to the sea. It may be too late for the magnitude of changes necessary to significantly improve the condition of the entire Aral Sea; it may already be beyond rescue (Micklin 1988).

How to Reverse the Trend: Recommendations for Water and Wetland Management Policy

The preceding examples illustrate how irrigated agriculture has shaped water utilization and allocation policies at the expense of some of the world's most ecologically valuable wetlands. Even the recommendations of prominent scientists and review boards, through such highly visible and global efforts as the Ramsar Convention, have done little to slow their continued degradation. This longstanding trend must be reversed if wetlands are to provide the critical habitat necessary for effective wildlife conservation and associated benefits to society. Two principal conditions must be met: (1) further degradation from existing irrigation activities must be prevented and adverse impacts mitigated, and (2) adequate planning and assessment for proposed irrigation projects must take place. Although these conditions are conceptually simple and straightforward, they are virtually impossible to achieve without first understanding a basic truth: irrigation policies typically revolve around perceived economic and societal benefits, many of which probably can not be justified environmentally or economically if examined closely. For example, the anticipated economic benefits of agricultural irrigation projects may be more than offset by environmental degradation and artificial water shortages (Livingstone and Campbell 1992, Contreras-Balderas and Lozano-Vilano 1994, Psychoudakis and others 1995). In some cases, large-scale irrigated agribusiness can actually contribute to high poverty rates among local communities (e.g., Grondin 1986). If wetland managers wish to achieve meaningful changes in water policy, then they should exploit these inherent weaknesses.

The question of how best to resolve water issues may be answered by examining two of the key perceptions that have guided policy decisions: (1) water is wasted if it goes out to sea or into a wetland (many farmers believe that water that passes them by is not being properly utilized), and (2) agriculture provides many economic benefits to many people—locally and far away—but wetlands provide few economic benefits and they are restricted to local people. These perceptions are clearly not true. One of the key wetland principles is that they often provide functions and values beyond their boundaries and far from adjacent ecosystems (Richardson 1994). Moreover, wetlands provide many benefits (not necessarily obvious to water policy makers) that may far exceed the value of agricultural crops, if carefully enumerated. For example, African floodplain wetlands provide agricultural, fishing, and fuelwood benefits that are over five times the value of formal irrigated agriculture (Thompson and Hollis 1995, Barbier and Thompson 1998). The relative economic value of wetlands becomes even greater if the apparent benefits provided by agriculture contain hidden costs. For example, irrigation production is often subsidized by public revenues (usually unknown to most taxpayers) through government supply of low-cost water, encouraging surplus production year after year, and government (artificial) markets for buying surpluses (Lemly 1994a). Other hidden costs include the taxpayer expense of building and maintaining infrastructure (dams, weirs, canals) and the expense of rehabilitating degraded rivers and wetlands, which in Australia amounted to A$3.32 billion (about US$280 million, in 1997 dollars) in 1994 alone (DEST 1996), not counting environmental subsidies (i.e., impacts on fauna and flora). Wetland managers and wildlife conservationists should develop an approach that illustrates the economic costs (liabilities) of agriculture and highlights the values (benefits) of wetlands. This can give wetlands and wildlife an equal or greater priority than agriculture in water policy decisions.

The goal is to fairly weigh up the benefits and costs of agriculture and conservation. A strong, perhaps indisputable case for conservation can be made based upon economic benefits, i.e., the monetary values deriving from consumptive (e.g., hunting, fishing, trapping, timber, grazing, subsistence) and nonconsumptive (e.g., ecological, aesthetical, heritage, cultural, biodiversity, conservation) uses of wetlands and wildlife. A compelling case is necessary because of a simple truth—political actions shaped by economic forces drive water policy. Agricultural interests typically have the ear (and often the wallet) of water policy makers. It is not enough for wetland managers and conservationists to be vocal and assertive about water needs for wildlife—this approach has failed time after time. A compelling economic case must be presented, supported by clear documentation, before recommendations for conservation are seriously considered or adopted. Regardless of whether the issue is wetlands, irrigation, or some other water use, the greater the associated economic values, the more attention it will receive by policy makers.

Some of the key elements in an economic-based approach to wetland management include: (1) providing policy makers with empirical data on the values (existing and potential revenues) of consumptive and nonconsumptive use of wildlife (e.g., recreation, hunting, fishing, birdwatching, maintenance of threatened or endangered species); (2) providing policy makers with data on the monetary benefits of preserving or expanding wetlands or restoring degraded wetlands to improve flood control, erosion/sediment/nutrient control, timber production, food production for humans (e.g., fish, shrimp, ducks), quantity and quality of water supplies for off-wetland uses (e.g., human consumption and domestic use); and (3) providing policy makers with data on the monetary value (losses) resulting from existing or potential degradation (economic benefits not being realized due to impacts from agricultural irrigation, subsidies, rising groundwater, salinity, erosion, etc).

Recognition of the importance of demonstrating the economic value of wetlands has led to a number of publications that outline the approaches that can be adopted (e.g., Barbier and others 1996, Costanza and others 1997). An excellent example of how to estimate wetland values for regional watershed planning is given by Hruby and others (1995). Wetland preservation produces two types of economic value: use value (consumptive or nonconsumptive) and nonuse (existence) value. Determining use values is fairly straightforward since the product or benefit carries an established, known cost. However, it is seldom done. It seems to be much easier to measure farm inputs/outputs in support of irrigation than to document wetland values. In the Macquarie Marshes, for example, no attempt was made to tabulate the economic benefit provided by floodplain grazing as a way to counter the economic analysis that showed how changes in water management could affect irrigation.

Estimating nonuse values is somewhat more elusive and depends upon societal perceptions of wetland functions, the culture and needs of the people who exploit them, and, to some extent, their location. However, it is critical that nonuse values be included because wetlands provide benefits to both the local and global economy that are not easily recognized and are often given too little weight in policy decisions (Costanza and others 1997). A survey of public attitudes and willingness to pay for wetland preservation/expansion is one method for ascribing values to nonuse attributes of wetlands (Loomis 1990, Whitehead and Blomquist 1991, Stevens and others 1995). Nonuse values can often exceed use values by a substantial margin. It is possible for these values to be considered in the same way we might believe in artistic values or heritage values or quality-of-life values. Including nonuse values in an economic approach to wetland management can make a key difference when agricultural interests are pitted against wetlands and wildlife. For example, the New South Wales government in Australia reached decisions for managing the Macquarie Marshes based in large part on ecological grounds (wildlife preservation) despite considerable lobbying by the irrigation industry with arguments that about A$35 million (about $US3 million) and about 500 jobs would be lost (MDBMC 1996, Morrison and Kingsford 1997).

To produce the data necessary for an economic-based approach, wetland managers may need to enlist the assistance of other professionals, particularly in gathering information for items 2 and 3. For example, comprehensive environmental assessments that incorporate geological, hydrological, and biological components should be made of existing irrigation projects to determine if the quantity or quality of water supplies reaching wetlands is unacceptably affected (e.g., through water diversions, pesticide contamination, salinization, subsurface irrigation drainage, etc.). Wildlife biologists and wetland scientists may determine if ecological viability of the wetland is threatened. Knowledgeable authorities in hydrology, aquatic toxicology, and ecological risk assessment could also broaden the evaluation and assessment (Lemly 1997, Lemly and Richardson 1997). The economic impact of detrimental ecological effects should be conveyed to management authorities and policy makers and also to the local communities that will be affected (educating the public can create a powerful force in support of conservation). This will illustrate the extent to which perceived benefits from agriculture are offset by the actual economic and societal benefits from wetlands. For example, Barbier and Thompson (1997) show that the economic benefits of developing all the irrigated agricultural schemes planned for the Hadejia-Jama'are Basin account for less than 14% of the economic losses that would result from reduced inundation of the floodplain.

Proposed agricultural irrigation projects should undergo a rigorous technical review (by experts in the various disciplines discussed above) to assess water demand and supply relationships and to determine the potential for water deficits, salinization, contamination, subsurface irrigation drainage, and impact on wetlands. Preventing wildlife problems through a preirrigation screening process will result in less adverse impacts to agriculture than correcting, at very high cost (usually borne by the taxpayers), environmental damage once it has occurred (Lemly 1993, 1994a). Identifying and evaluating potential problems is the key. For example, information on local geology can be used to determine the location of impermeable subsurface soils and identify areas that would become waterlogged and produce irrigation drainage that could contain potentially harmful levels of soil trace elements (e.g., selenium, arsenic, boron). These areas should probably not be irrigated.

Projects that involve water diversions impose a high degree of environmental risk because they can greatly modify the quality of water reaching or residing in wetlands even though water quantity issues may be the most obvious concern and may seemingly be accounted for. As the previous case examples illustrate, terminal wetlands are some of the most valuable and highly recognized for wildlife conservation, and they are also especially vulnerable to progressive declines in water quality because of evaporative concentration of salts and contaminants as freshwater inflows are reduced. In the Lahontan Valley wetlands of Nevada, for example, gradual changes in aquatic vegetation and declines in wildlife food plants and fish due to increased salinity and buildup of contaminants took place over a 40-year period, even in the best marshes where water levels were maintained similar to historic conditions (Hoffman and others 1990, Hallock and Hallock 1993, Lemly 1994a). A cascade of subtle, but important, biological effects can occur if water quality is changed. Thus, even projects that will apparently not cause water quantity problems must be evaluated very cautiously because there are many hidden dangers associated with diverting freshwater supplies away from wetlands.

Proper analysis of wetland functions at an ecosystem scale can determine the necessary hydrologic regime and also identify risks from various amounts of water reduction (Lemly 1997, Lemly and Richardson 1997). Simply maintaining flooded conditions may not suffice because some wetland flora and fauna require a seasonal dry period. Moreover the timing of water inputs or reductions in flow (hydroperiod) may conflict with the normal seasonal occupancy and utilization by wildlife. Both the biological system of a wetland and its hydrological underpinnings must be understood before adequate plans can be made to preserve it. An environmental assessment that integrates wetland ecology, hydrology, geomorphology, and soils can greatly improve the evaluation of proposed water development projects and identify likely impacts to wildlife. Importantly, this approach can be used to determine whether a water management scenario poses an unreasonable risk (biologically defined) to the sustainability of a particular wetland (Lemly and others 1998).

Conclusions

The conflict between irrigated agriculture and wildlife conservation has reached a critical point on a global scale. Many key wetlands are now a mere shadow of what they once were in terms of biodiversity and wildlife production. Not only does local wildlife suffer, including extinction of highly insular species, but a ripple effect impacts migratory birds literally around the world. Pleas and declarations made by scientists and environmentalists calling for wetland preservation have gone largely unheeded. Recent developments such as the Biodiversity Convention of the United Nations Conference in Rio de Janeiro (Denny 1994) show willingness to resolve environmental issues related to wetlands. Agenda 21, a global partnership for sustainable development in the next century, was established. Although the goals are noble, conferences such as this may merely establish political correctness rather than institute meaningful changes in environmental management policy. "Care must be taken that the euphoria born at the Rio Conference is not allowed to degenerate into a series of platitudes in which words like biodiversity and sustainable development become political words of convenience rather than words of true meaning" (Denny 1994). This quote highlights the key failing of past efforts: much is said and written, but it is business as usual on Monday morning. Moreover, the track record established over the past 40 years suggests that sustainable development is a political code name for perpetual growth, used strategically to make development more palatable to those who would oppose it (Willers 1994).

Agricultural threats to wetlands and wildlife conservation are often disguised within a sustainable development scenario, i.e., that continued growth and development are compatible with environmental constraints. As noted by Pearce and others (1989), "sustainable development has come to mean whatever suits the advocacy of the individual or group concerned." Advocacy for sustainable agriculture under a false pretense of environmental compatibility has been a principal factor guiding water policy decisions for decades. Environmental management has been intense and largely in one direction—toward agricultural development. Yet, the recurring result has been that so-called sustainable development guaranteed the deterioration of wetland ecosystems and loss of biodiversity.

Recent surveys reveal that steady growth of irrigated agriculture is continuing to occur (e.g., Anonymous 1997). Water demands for domestic and industrial use will no doubt expand substantially over the next 30 years (Postel and others 1996). However, overcoming the water policy inertia exerted by agriculture in order to achieve wetland preservation goals is not a futile proposition. In many cases, informing and educating local communities can be a pivotal factor in water management decisions. Perhaps the most important message we wish to convey in this paper is that ecological disasters caused by agricultural irrigation are not inevitable. Rural communities whose rivers and wetlands have not yet been exploited can mobilize and do something before it is too late. Changes can be brought about to improve the management and ecological condition of those that have been exploited. With cooperation and strategic planning, local citizens and wetland managers can have a significant effect on how water policies are developed and implemented. Efforts at the local level, on a case-by-case basis, are what will cause the changes necessary for wildlife conservation. Detailed economic valuation of wetland resources and application of the resultant ecosystem capital in water negotiations should be the major focus of these efforts.

A clear conclusion from this paper is that any form of conservation initiative for wetlands must encompass activities taking place within whole watersheds. Achieving success will depend on how well an integrated system for the allocation of water among the different parts of the basin can be developed and implemented. Water management plans that acknowledge and explicitly incorporate the water requirements of wetlands as well as those associated with agriculture, domestic supplies, and industry are necessary. Negotiating agreements that satisfy all parties will be difficult at best. However, the reversal of degradation in Australia's Macquarie Marshes and the progress evident in restoring Nigerian floodplain wetlands demonstrate that ecologically sound water management policies are attainable for wetlands on a large scale despite widely divergent interests and priorities. We hope that this paper will help in on-going efforts to develop water policies that will conserve wetlands and wildlife around the world.

Acknowledgments

We thank the following individuals for providing review comments that improved this paper: Drs. S. V. Briggs, C. A. Dolloff, M. T. Maher, Mr. B. Johnson, and Mr. G. Polet. Information on impacts of agriculture on Australian wetlands was provided by A. Corrick, A. Jensen, S. A. Halse, and J. G. Blackman. We also acknowledge the support and encouragement of the Hadejia-Nguru Wetlands Conservation Project and IUCN during the course of research in northeast Nigeria.

Literature Cited

Acreman, M. C. 1994. The role of artificial flooding in the integrated development of river basins in Africa. Pages 35–44 *in* C. Kirby and W. R. White (eds.), Integrated river basin development. Wiley, Chichester, UK.

Adam, P. 1995. Urbanization and transport. Pages 55–75 *in* R. Bradstock, T. D. Auld, D. A. Keith, R. T. Kingsford, D. Lunney, and D. Sivertsen (eds.), Conserving biodiversity: Threats and solutions. Surrey Beatty & Sons, Sydney, New South Wales, Australia.

Adams, W. M. 1992. Wasting the rain: Rivers, people and planning in Africa. Earthscan, London.

Adams, W. M. 1993. The wetlands and conservations. Pages 211–214 *in* G. E. Hollis, W. M. Adams, and M. Aminu-Kano (eds.), The Hadejia-Nguru Wetlands: Environment, economy and sustainable development of a Sahelian floodplain wetland. IUCN, Gland, Switzerland.

Adams, W. M. 1996. Economics and hydrological management of African floodplains. Pages 21–33 *in* M. C. Acreman, and G. E. Hollis (eds.), Water management and wetlands in Sub-Saharan Africa. IUCN, Gland, Switzerland.

Adams, W. M., M. Garba Boyi, and G. E. Hollis. 1993a. Natural resources of the Hadejia-Jama'are floodplain. Pages 11–18 *in* G. E. Hollis, W. M. Adams, and M. Aminu-Kano (eds.), The Hadejia-Nguru Wetlands: Environment, economy and sustainable development of a Sahelian floodplain wetland. IUCN, Gland, Switzerland.

Adams, W. M., G. E. Hollis, and I. A. Hadejia. 1993b. Management of the river basin and irrigation. Pages 119–148 *in* G. E. Hollis, W. M. Adams, and M. Aminu-Kano (eds.), The Hadejia-Nguru Wetlands: Environment, economy and sustainable development of a Sahelian floodplain wetland. IUCN, Gland, Switzerland.

Akinsola, O. A., A. U. Ezealor, and G. Polet. 1996. Conservation of waterbirds in the Hadejia-Nguru Wetlands, Nigeria: Current efforts and problems. Paper presented at the 9th Pan African ornithological congress, Accra, Ghana, 1–8 December 1996.

Aladin, N. V., I. S. Plotnikov, and W. T. W. Potts. 1995. The Aral Sea dessication and possible ways of rehabilitating and conserving its northern part. *Environmetrics* 6:17–29.

Anonymous. 1997. 1996 irrigation survey reflects steady growth. *Irrigation Journal* Jan/Feb.

Barbier, E. B., and J. R. Thompson. 1998. The value of water: Floodplain versus large-scale irrigation benefits in northern Nigeria. *Ambio* 27:434–440.

Barbier, E. B., W. M. Adams, and K. Kimmage. 1991. Economic evaluation of wetland benefits: The Hadejia-Jama'are floodplain, Nigeria. London Environmental Economics Centre discussion paper DP 91-02. International Institute for Environment and Development, London.

Barbier, E. B., D. Knowler, and M. C. Acreman. 1996. Economic valuation of wetlands: A guide for policy makers and planners. IUCN Publications Unit, Cambridge, UK.

Barmuta, L. A., R. Marchant, and P. S. Lake. 1992. Degradation of Australian streams and progress towards conservation and management in Victoria. Pages 65–79 *in* P. J. Boon, P. Calow, and G. E. Petts (eds.), River Conservation and Management. John Wiley & Sons, New York.

Bennett, M. J. A., and J. Green. 1993. Estimating the water requirements of the lower Gwydir wetlands. New South Wales Department of Water Resources, Sydney, New South Wales, Australia.

Blackman, J. G., T. W. Perry, G. I. Ford, S. A. Craven, S. J. Gardiner, and R. J. De Lai. 1996. Queensland. A directory of important wetlands in Australia, 2nd ed. Australian Nature Conservation Agency, Canberra, Australia.

Brander, D. 1987. Environmental changes in the southern Macquarie Marshes: 1934 to 1987. Honours thesis, University of New South Wales, New South Wales, Australia.

Bren, L. 1988. Effects of river regulation on flooding of a riparian red gum forest on the river Murray, Australia. *Regulated Rivers* 2:65–77.

Bren, L. 1990. Red gum forests. Pages 231–242 *in* N. Mackay and D. Eastburn (eds.), The Murray. Murray Darling Basin Commission, Canberra, Australia.

Bren, L. 1992. Tree invasion of an intermittent wetland in relation to changes in the flooding frequency of the River Murray, Australia. *Australian Journal of Ecology* 17:395–408.

Brereton, G. 1994. Summary report. Macquarie Marshes management strategy—stage 1, biophysical investigations, natural resources management strategy. New South Wales Department of Water Resources, Dubbo, New South Wales, Australia.

Bruwer, C., C. Poultney, and Z. Nyathi. 1996. Community based hydrological management of the Phongolo floodplain. Pages 199–211 *in* M. C. Acreman, and G. E. Hollis (eds.), Water management and wetlands in sub-Saharan Africa. IUCN, Gland, Switzerland.

Briggs, S. V., P. F. Hodgson, and P. Ewin. 1994. Changes in populations of waterbirds on a wetland following water storage. *Wetlands (Australia)* 13:36–48.

Briggs, S. V., S. A. Thornton, and W. G. Lawler. 1997. Relationship between hydrological control of river red gum wetlands and waterbird breeding. *Emu* 97:31–42.

Buckmaster, D. E., I. Hastings, and P. L. Rogan. 1979. Inquiry into water allocations in northern Victoria. Fish and Wildlife Victoria, Paper number 21. Melbourne, Victoria, Australia.

Clifton, D. G., and R. J. Gilliom. 1989. Sources and concentrations of dissolved salts and selenium in the San Joaquin River and its tributaries, California, October 1985 to March

1987. Water-resources investigations report 88-4217. US Geological Survey, Sacramento, California.

Contreras-Balderas, S., and M. L. Lozano-Vilano. 1994. Water, endangered fishes, and development perspectives in arid lands of Mexico. *Conservation Biology* 8:379–387.

Cooper, R. P. 1954. Birds of the Macquarie Marshes, New South Wales. *Memoirs of the National Museum of Victoria* 19:137–163.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253–260.

Cunningham, G. 1997. Macquarie Marshes grazing study—1996. Unpublished final report to the Macquarie Marshes Catchment Committee. Sydney, New South Wales, Australia.

Debus, S. J. 1989. Moree Watercourse. *RAOU Newsletter* 81:5.

Denny, P. 1994. Biodiversity and wetlands. *Wetlands Ecology and Management* 3:55–61.

DEST (Department of Sport and Territories). 1996. Subsidies to the use of natural resources. Department of Sport and Territories, Commonwealth of Australia, Canberra, Australia.

DLWC (Department of Land and Water Conservation). 1995. Central and north west regions water quality program 1994/95 report on nutrients and general water quality. Report No. TS95.088. Water Quality Services Unit, Technical Services Division, Department of Land and Water Conservation, Orange, New South Wales, Australia.

DLWC and NPWS (Department of Land and Water Conservation and National Parks and Wildlife Service). 1996. Macquarie Marshes water management plan 1996. National Parks and Wildlife Service and Department of Land and Water Conservation, Hurstville, New South Wales, Australia.

DPI (Department of Primary Industries). 1996. Unregulated flow studies for the Condamine/Balonne/Culgoa River system. Report for the Dumaresq-Barwon Border Rivers Commission. Department of Primary Industries, Brisbane, Queensland, Australia.

Drijver, C. A., and M. Marchand. 1985. Taming the floods: Environmental aspects of floodplain development in Africa. Centre for Environmental Studies, University of Leiden, Leiden, The Netherlands.

Drijver, C. A., and W. F. Rodenburg. 1988. Water management at the cross roads: The case of the Sahelian Wetlands. Paper presented at the international symposium of hydrology of wetlands in semi-arid and arid regions, Seville, Spain, May 1988.

Drijver, C. A., and C. J. Van Wetten. 1992. Sahel Wetlands 2020: Changing development policies or losing Sahel's best resources. Centre of Environmental Science, University of Leiden, Leiden, The Netherlands.

Dugan, P. 1990. Wetland conservation: A review of current issues and required action. IUCN, Gland, Switzerland.

DWR (Department of Water Resources). 1991. Water resources of the Macquarie Valley. Department of Water Resources, Sydney, New South Wales, Australia.

DWR (Department of Water Resources). 1994. Central and north west regions water quality program 1993/94 report on nutrients and general water quality. Report No. TS94.088. Water Quality Unit, Technical Services Division, Department Water Resources, Sydney, New South Wales, Australia.

DWR and NPWS (Department of Water Resources and National Parks and Wildlife Service). 1986. Water management plan for the Macquarie Marshes. Department of Water Resources and National Parks and Wildlife Service, Hurstville, New South Wales, Australia.

EPA (New South Wales Environment Protection Authority). 1995. New South Wales state of the environment 1995. New South Wales Environment Protection Authority, Sydney, New South Wales, Australia.

FAO (Food and Agriculture Organization). 1993. Nigeria: Irrigation project: Identification report. Report No. 30/93 CP NIR 56. Food and Agriculture Organization, United Nations, Rome, Italy.

Frayer, W. E., D. D. Peters, and H. R. Pywell. 1989. Wetlands of the California Central Valley: Status and trends—1939 to mid-1980's. US Fish and Wildlife Service, Portland, Oregon.

Froend, R. H., E. M. Heddle, D. T. Bell, and A. J. McComb. 1987. Effects of salinity and waterlogging on the vegetation of Lake Toolibin, Western Australia. *Australian Journal of Ecology* 12:281–298.

Garba Boyi, M., and G. Polet. 1996a. Birdlife under water stress: The case of the Hadejia-Nguru Wetlands, northern Nigeria. Pages 147–152 *in* R. D. Belilfuss, W. R. Tarboton, and N. N. Gichuki (eds.). Proceedings of the African crane and wetland training workshop, Maun, Botswana, 8–15 August 1993. International Crane Foundation, Baraboo, Wisconsin.

Garba Boyi, M. and G. Polet. 1996b. Afrotropical Anatidae population trends in the Hadejia-Nguru Wetlands, northern Nigeria (1988–1994). *Gibier Faune Sauvage, Game and Wildlife* 13:587–598.

Garba Boyi, M., N. D. Burgess, and K. G. Smith. 1992. Ornithological significance of the Hadejia-Nguru Wetlands, northern Nigeria. Paper presented at the 8th Pan African ornithological congress, Burundi.

Gilbert, C. L., and J. B. Ramey. 1995. Riverine wetlands of the Alberta prairie. Alberta Parks and Wildlife, Edmonton, Alberta.

Gilmer, D. S., M. R. Miller, R. D. Bauer, and J. R. LeDonne. 1982. California's Central Valley wintering waterfowl: Concerns and challenges. *Transactions of the North American Wildlife and Natural Resources Conference* 47:441–452.

Goodrick, G. 1970. A survey of wetlands of coastal New South Wales. C.S.I.R.O. Division of Wildlife Research Technical Memorandum Number 5. C.S.I.R.O., Canberra, Australia.

Greenspan, R. L. 1988. Fish remains. Pages 312–326 *in* C. Raven and R. G. Elston (eds.), Preliminary investigations in Stillwater Marsh—human prehistory and geoarchaeology. US Fish and Wildlife Service, Portland, Oregon.

Grondin, B. 1986. Does big agribusiness spell community doom? *California Farmer* May.

Hallock, R. J., and L. L. Hallock. 1993. Detailed study of irrigation drainage in and near wildlife management areas, west-central Nevada, 1987-90. Part B. Effect on biota in Stillwater and Fernley Wildlife Management Areas and other nearby wetlands. Water-Resources Investigations Report 92-4024B. US Geological Survey, Carson City, Nevada.

Halse, S. A. 1987. Probable effect of increased salinity on the waterbirds of Lake Toolibin. Technical report number 15. Department of Conservation and Land Management, Perth, Western Australia.

Halse, S. A. 1989. Wetlands of the Swan Coastal Plain past and present. Pages 105–108 *in* G. Lowe (ed.), Swan coastal groundwater management conference—proceedings. Western Australian Water Resources Council publication No. 1/89. Perth, Western Australia.

Halse, S. A., G. B. Pearson, and S. Patrick. 1993. Vegetation of depth-gauged wetlands in nature reserves of south-west Western Australia. Technical report number 30. Department of Conservation and Land Management, Perth, Western Australia.

Hamilton, S. J., K. J. Buhl, F. A. Bullard, and S. F. McDonald. 1996. Evaluation of toxicity to larval razorback sucker of selenium-laden food organisms from Ouray National Wildlife Refuge on the Green River, Utah. US Fish and Wildlife Service, Denver, Colorado.

Hoffman, R. J., R. J. Hallock, T. G. Rowe, M. S. Lico, H. L. Burge, and S. P. Thompson. 1990. Reconnaissance investigation of water quality, bottom sediment, and biota associated with irrigation drainage in and near Stillwater Wildlife Management Area, Churchill County, Nevada, 1986-87. Water-resources investigations report 89-4105. US Geological Survey, Carson City, Nevada.

Hoffman, S. E., N. J. Williams, and A. I. Herson. 1986. The Kesterson story. Proceedings of the first biennial conference, pp. 1–9. National Water Supply Improvement Association, Springfield, Virginia.

Hollis, G. E. 1986. The modeling and management of the internationally important wetland at Garaet El Ichkeul, Tunisia. IWRB special publication number 4. International Waterfowl Research Bureau, Slimbridge, UK.

Hollis, G. E., and M. C. Acreman. 1994. The functions of wetlands within integrated river basin development: International perspectives. Pages 351–365 *in* C. Kirby and W. R. White (eds.), Integrated river basin development. Wiley, Chichester, UK.

Hollis, G. E., and J. R. Thompson. 1993a. Hydrological model of the floodplain. Pages 69–79 *in* G. E. Hollis, W. M. Adams, and M. Aminu-Kano (eds.), The Hadejia-Nguru Wetlands: Environment, economy and sustainable development of a Sahelian floodplain wetland. IUCN, Gland, Switzerland.

Hollis, G. E., and J. R. Thompson. 1993b. Water resource developments and their hydrological impacts. Pages 149–190 *in* G. E. Hollis, W. M. Adams, and M. Aminu-Kano (eds.), The Hadejia-Nguru Wetlands: Environment, economy and sustainable development of a Sahelian floodplain wetland. IUCN, Gland, Switzerland.

Hollis, G. E., W. M. Adams, and M. Aminu-Kano (eds.). 1993a. The Hadejia-Nguru Wetlands: Environment, economy and sustainable development of a Sahelian floodplain wetland. IUCN, Gland, Switzerland.

Hollis, G. E., S. J. Penson, J. R. Thompson, and A. R. Sule. 1993b. Hydrology of the river basin. Pages 19–67 *in* G. E. Hollis, W. M. Adams, and M. Aminu-Kano (eds.), The Hadejia-Nguru Wetlands: Environment, economy and sustainable development of a Sahelian floodplain wetland. IUCN, Gland, Switzerland).

Hothem, R. L., and D. Welsh. 1994. Contaminants in eggs of aquatic birds from the Grasslands of central California. *Archives of Environmental Contamination and Toxicology* 27:180–185.

Hruby, T., W. E. Cesanek, and K. E. Miller. 1995. Estimating relative wetland values for regional planning. *Wetlands* 15:93–107.

Hull, G. 1996. Victoria. Pages 605–757 *in* R. Blackley, S. Usback, and K. Langford (eds.), A directory of important wetlands in Australia, 2nd ed. Australian Nature Conservation Agency, Canberra, Australia.

Jensen, A., P. Hoey, P. Kopli, R. Shepherd, M. Till, and M. Weinert. 1983. The effects of drainage on groundwater behaviour in counties Cardwell and Buckingham and the effect on the Coorong. Unpublished report to Minister of Water Resources, 1981–1983. Adelaide, South Australia.

Keyte, P. 1992. Lower Gwydir wetland—preliminary identification of resource management issues—discussion paper. Lower Gwydir wetland management plan steering committee. New South Wales Department of Water Resources, Sydney, New South Wales, Australia.

Kimmage, K. 1991. The evolution of the 'wheat trap': The Nigerian wheat boom. *Africa* 60:471–500.

Kingsford, R. T. 1995. Ecological effects of river management in New South Wales. Pages 144–161 *in* R. Bradstock, T. D. Auld, D. A. Keith, R. T. Kingsford, D. Lunney, and D. Sivertsen (eds.), Conserving biodiversity: Threats and solutions. Surrey Beatty and Sons, Sydney, New South Wales, Australia.

Kingsford, R. T., and R. F. Thomas. 1995. The Macquarie Marshes in arid Australia and their waterbirds: A 50 year history of decline. *Environmental Management* 19:867–878.

Kirkpatrick, J. B., and P. A. Tyler. 1988. Wetlands and their conservation. Pages 1–16 *in* A. J. McComb and P. S. Lake (eds.), The conservation of Australian wetlands. Surrey Beatty and Sons, Sydney, New South Wales, Australia.

Knapton, J. R., W. E. Jones, and J. W. Sutphin. 1987. Reconnaissance investigation of the quality of water, bottom sediment, and biota in the Sun River Project, West Central Montana. Water-resources investigations report 87-4244. US Geological Survey, Missoula, Montana.

Lambing, J. H., W. E. Jones, and J. W. Sutphin. 1987. Reconnaissance investigation of the quality of water, bottom sediment, and biota in the Bowdoin National Wildlife Refuge and ajacent areas of the Milk River Irrigation Project, Northeastern Montata. Water-resources investigations report 878-4243. US Geological Survey, Missoula, Montana.

Lane, J. A. K., and A. J. McComb. 1988. Western Australian wetlands. Pages 127–146 *in* A. J. McComb and P. S. Lake (eds.), Conservation of Australian wetlands. Surrey Beatty and Sons, Sydney, New South Wales, Australia.

Lemly, A. D. 1993. Subsurface agricultural irrigation drainage: The need for regulation. *Regulatory Toxicology and Pharmacology* 17:157–180.

Lemly, A. D. 1994a. Irrigated agriculture and freshwater wetlands: A struggle for coexistence in the western United States. *Wetlands Ecology and Management* 3:3–15.

Lemly, A. D. 1994b. Agriculture and wildlife: Ecological implications of subsurface irrigation drainage. *Journal of Arid Environments* 28:85–94.

Lemly, A. D. 1996. Identifying and reducing environmental risks from agricultural irrigation drainage in developing countries. *Proceedings of the Congress of Toxicology in Developing Countries* 3:177–190.

Lemly, A. D. 1997. Risk assessment as an environmental management tool: Considerations for freshwater wetlands. *Environmental Management* 21:343–358.

Lemly, A. D., and C. J. Richardson. 1997. Guidelines for risk assessment in wetlands. *Environmental Monitoring and Assessment* 47:117–134.

Lemly, A. D., S. E. Finger, and M. K. Nelson. 1993. Sources and impacts of irrigation drainwater contaminants in arid wetlands. *Environmental Toxicology and Chemistry* 12:2265–2279.

Lemly, A. D., R. Best, W. Crumpton, M. Henry, D. Hook, G. Linder, P. Masscheleyn, H. Peterson, T. Salt, and R. Stahl. 1999. An ecosystem approach to risk assessment in freshwater wetlands. Chapter 4 *in* M. A. Lewis and others (eds.), Ecotoxicology and risk assessment for wetlands. SETAC Press, Pensacola, Florida.

Livingstone, A. J., and I. A. Campbell. 1992. Water supply and urban growth in southern Alberta: Constraint or catalyst? *Journal of Arid Environments* 23:335–349.

Loomis, J. B. 1990. The economic value of water to wildlife and fisheries in the San Joaquin Valley. *Transactions of the North American Wildlife and Natural Resources Conference* 55:202–213.

Lothian, J. A., and W. D. Williams. 1988. Wetland conservation in South Australia. Pages 147–166 *in* A. J. McComb and P. S. Lake (eds.), The Conservation of Australian wetlands. Surrey Beatty and Sons, Sydney, New South Wales, Australia.

Maheshwari, B. L., K. F. Walker, and T. A. McMahon. 1995. Effects of regulation on the flow regime of the River Murray, Australia. *Regulated Rivers—Research & Management* 10: 15–38.

Mamza, J. U. 1995. Nature conservation in the Komadugu-Yobe Basin. Pages 39–48 *in* M. Aminu-Kano (ed.), The critical water resources of the Komadugu-Yobe Basin. Proceedings of a workshop on the management of the water resources of the Komadugu-Yobe Basin. National Institute for Policy and Strategic Studies, Kuru, Jos, Nigeria, and Hadejia-Nguru Wetlands Conservation Project, Nguru, Nigeria.

Marchant, S., and P. J. Higgins. 1990. Handbook of Australian, New Zealand and Antarctic birds, Volume 1. Ratites to ducks. Oxford University Press, Melbourne, Victoria, Australia.

Margolin, S. 1979. Liability under the Migratory Bird Treaty Act. *Ecological Law Quarterly* 7:989–1010.

Marshall, E. 1985. Selenium poisons refuge, California politics. *Science* 229:144–146.

McHugh, S. 1996. Cottoning on. Stories of Australian cotton-growing. Hale & Iremonger, Sydney, New South Wales, Australia.

MDBMC (Murray-Darling Basin Ministerial Council). 1996. Setting the cap. Report of the independent audit group. Murray-Darling Basin Ministerial Council, Canberra, Australia.

Media Associates. 1997. Where the river runs dry—featuring the Macquarie Marshes. Video (42 minutes). Media Associates, Canberra, Australia.

Micklin, P. P. 1988. Desiccation of the Aral Sea: A water management disaster in the Soviet Union. *Science* 241:1170–1176.

Moore, S. B., J. Winckel, S. J. Detwiler, S. A. Klasing, P. A. Gaul, A. R. Kanim, B. E. Kesser, A. B. Debevac, A. Beardsley, and L. A. Puckett. 1990. Fish and wildlife resources and agricultural irrigation drainage in the San Joaquin Valley, California. San Joaquin Valley Drainage Program, Sacramento, California.

Morrison, M., and R. T. Kingsford. 1997. The management of inland wetlands and river flows and the importance of economic valuation in New South Wales. *Wetlands (Australia)* 16:83–98.

Moyle, P. B. 1976. Inland fishes of California. University of California Press, Berkeley, California.

Muslim, I., and A. I. Umar. 1995. Water resources and agricultural development in Jigawa State. Pages 49–62 *in* M. Aminu-Kano (ed.), The critical water resources of the Komadugu-Yobe Basin. Proceedings of a workshop on the management of the water resources of the Komadugu-Yobe Basin. National Institute for Policy and Strategic Studies, Kuru, Jos, Nigeria, and Hadejia-Nguru Wetlands Conservation Project, Nguru, Nigeria.

N'diaye, A. 1997. Ecological problems caused by dams in West Africa: Case study of Djoudj National Park, Senegal. Pages 142–145 *in* R. C. Prentice and R. P. Jaensch (eds.), Development policies, plans and wetlands. Proceedings of workshop 1 of the international conference on wetlands and development, Kuala Lumpur, Malaysia, 9–13 October 1995. Wetlands International, Kuala Lumpur, Malaysia.

Nell, J. M. 1987. Data for selected pesticides and volatile organic compounds for wells in the western San Joaquin Valley, California, February to July 1985. Open-file report 87-48. US Geological Survey, Sacramento, California.

Newman, P., B. Birrell, D. Holmes, C. Mathers, P., Newton, G., Oakley, A., O'Connor, B., Walker, A., Spessa, and D. Tait. 1996. Human settlements. Pages 1–57 *in* N. Alexander and R. Taylor (eds.), Australia: State of environment 1996. An independent report presented to the Commonwealth Minister for the Environment by the State of the Environment, Advisory Council. CSIRO Publishing, Melbourne, Victoria, Australia.

Norman, F. I., and A. H. Corrick. 1988. Wetlands in Victoria: A brief review. Pages 17–34 *in* A. J. McComb and P. S. Lake (eds.), The conservation of Australian wetlands. Surrey Beatty & Sons, Sydney, New South Wales, Australia.

NRC (Natural Resources Council of South Australia). 1993. Upper south east dryland salinity and flood management plan—draft environmental impact statement—for public comment. Published by Upper South East Dryland Salinity and Flood Management Plan Steering Committee, Adelaide, South Australia.

O'Brien, J. M. 1995. Central and north west regions water quality program: 1994/95 Macquarie cotton industry benchmarking. Technical services division report TS95.029. Department of Land & Water Conservation, Orange, New South Wales, Australia.

Ohlendorf, H. M., R. L. Hothem, T. W. Aldrich, and A. J. Krynitsky. 1987. Selenium contamination of the Grasslands, a major California waterfowl area. *The Science of the Total Environment* 66:169–183.

Olofin, E. A. 1996. Dam-induced drying-out of the Hadejia-Nguru Wetlands, northern Nigeria and its implications for the fauna. Pages 141–145 *in* R. D. Belilfuss, W. R. Tarboton, and N. N. Gichuki (eds.), Proceedings of the African crane and wetland training workshop, Maun, Botswana, 8–15 August 1993. International Crane Foundation, Baraboo, Wisconsin.

Paijmans, K. 1981. The Macquarie Marshes of inland northern New South Wales. CSIRO Division of Land Use Research Technical Paper No. 41, Canberra, Australia.

Pearce, D., A. Markandja, and E. B. Barbier. 1989. Blueprint for a green economy. Earthscan, London.

Pearce, F. 1995. Poisoned waters. *New Scientist* October 21: 29–33.

Perennou, C. 1991. Les Récensement Internationaux d'Oiseax d'Eau en Afrique Tropicale. IWRB Special Publication No. 15. International Waterfowl and Wetlands Research Bureau, Slimbridge, UK.

Perera, J. 1993. A sea turns to dust. *New Scientist* October 21:24–27.

Peterson, D. A., W. E. Jones, and A. G. Morton. 1988. Reconnaissance investigation of water quality, bottom sediment, and biota associated with irrigation drainage in the Kendrick Reclamation Project area, Wyoming, 1986–87. Water-resources investigations report 87-4255. US Geological Survey, Cheyenne, Wyoming.

Polet, G., and J. R. Thompson. 1996. Maintaining the floods: Hydrological and institutional aspects of managing the Komadugu-Yobe River Basin and its floodplain wetlands. Pages 73–100 *in* M. C. Acreman and G. E. Hollis (eds.), Water management and wetlands in sub-Saharan Africa. IUCN, Gland, Switzerland.

Polet, G., I. S. Dutse, O. A. Akinsola, and M. Garba Boyi. 1997. The 1997 survey of waterfowl and water related birds of the Hadejia-Nguru Wetlands, Nigeria. Hadejia-Nguru Wetlands Conservation Project, Nguru, Nigeria.

Postel, S. L., G. C. Daily, and P. R. Ehrlich. 1996. Human appropriation of renewable fresh water. *Science* 271:785–788.

Presser, T. S. 1994. The Kesterson effect. *Environmental Management* 18:437–454.

Presser, T. S., M. A. Sylvester, and W. H. Low. 1994. Bioaccumulation of selenium from natural geologic sources in western states and its potential consequences. *Environmental Management* 18:423–436.

Pressey, R. L. 1989. Wetlands of the Lower Clarence Floodplain, northern coastal New South Wales. *Proceedings of the Linnaean Society of New South Wales* 111:143–155.

Pressey, R. L. 1990. Wetlands. Pages 167–181 *in* N. Mackay and D. Eastburn (eds.), The Murray. Murray Darling Basin Commission, Canberra, Australia.

Pressey, R. L., and J. H. Harris. 1988. Wetlands of New South Wales. Pages 35–57 *in* A. J. McComb and P. S. Lake (eds.), Conservation of Australian wetlands. Surrey Beatty & Sons, Sydney, New South Wales, Australia.

Pressey, R. L., and M. J. Middleton. 1982. Impacts of flood mitigation works on coastal wetlands in New South Wales. *Wetlands* 2:27–44.

Preston, W. L. 1981. Vanishing landscapes: Land and life in the Tulare Lake Basin. University of California Press, Berkeley.

Psychoudakis, A., S. Papoutsi-Psychoudaki, and A. M. M. McFarquhar. 1995. An economic assessment of an irrigation project affecting a Greek wetland. *Wetlands Ecology and Management* 3:225–232.

Raven, C., and R. G. Elston. 1988. Preliminary investigations in Stillwater Marsh—human prehistory and geoarchaeology, Volumes 1 and 2. US Fish and Wildlife Service, Portland, Oregon.

Raven, C., and R. G. Elston. 1989. Preliminary investigations in Stillwater Marsh—human prehistory and geoarchaeology, Volume 3. US Fish and Wildlife Service, Portland Oregon.

Raven, C., and R. G. Elston. 1990. Preliminary investigations in Stillwater Marsh—human prehistory and geoarchaeology, Volume 4. US Fish and Wildlife Service, Portland Oregon.

Reisner, M. 1986. Cadillac Desert: The American West and its disappearing water. Viking-Penguin Press, New York.

Richardson, C. J. 1994. Ecological functions and human values in wetlands: A framework for assessing forestry impacts. *Wetlands* 14:1–9.

Robertson, A. I. 1997. Land-water linkages in floodplain river systems: The influence of domestic stock. Pages 207–218 *in* N. Klomp and I. Lunt (eds.), Frontiers in ecology. Elsevier Science, Oxford, UK.

Roe, G. P., J. E. Nitshke, S. H. Nosworthy, and L. R. Speher. 1980. Environmental impact study on the effect of drainage in the south east of South Australia. South Eastern Drainage Board, Adelaide, South Australia.

Saunders, D., A. Beattie, S. Eliot, M. Fox, B. Hill, B. Pressey, D. Veal, J. Venning, M. Maliel, and C. Zammit. 1996. Biodiversity. Pages 1–68 *in* N. Alexander and R. Taylor (eds.), Australia: State of environment 1996. An independent report presented to the Commonwealth Minister for the Environment by the State of the Environment, Advisory Council. CSIRO Publishing, Melbourne, Victoria, Australia.

Schroeder, R. A., D. U. Palawski, and J. P. Skorupa. 1988. Reconnaissance investigation of water quality, bottom sediment, and biota associated with irrigation drainage in the Tulare Lake Bed area, southern San Joaquin Valley, California, 1986–87. Water-resources investigations report 88-4001. US Geological Survey, Sacramento, California.

Scott, D. A. and P. M. Rose. 1996. Atlas of Anatidae populations in Africa and western Eurasia. Wetlands International, Wageningen, The Netherlands.

See, R. B., D. A. Peterson, and P. Ramirez, Jr. 1992a. Physical, chemical, and biological data for detailed study of irrigation drainage in the Kendrick Reclamation Project area, Wyoming, 1988–90. Open-file report 91-533. US Geological Survey, Cheyenne, Wyoming.

See, R. B., D. L. Naftz, D. A. Peterson, J. G. Crock, J. A. Erdman, R. C. Severson, P. Ramirez, Jr., and J. A. Armstrong. 1992b. Detailed study of selenium in soil, representative plants, water, bottom sediment, and biota in the Kendrick Reclamation Project area, Wyoming, 1988–90. Water-resources investigations report 91-4131. US Geological Survey, Cheyenne, Wyoming.

Shelton, N. 1984. Wetlands of the north: A conservation challenge. *Nigerian Conservation Foundation Newsletter* December:13–17.

Simpson, J. H. 1876. Report of explorations across the Great Basin of the Territory of Utah for a direct wagon-route from Camp Floyd to Genoa, in Carson Valley, in 1859. Reprint of US Army Engineer Department Document. University of Nevada Press, Reno, Nevada.

SKPPL (Sinclair Knight Partners Pty., Ltd.). 1984. New South Wales Inland Rivers Flood Plain Management Studies—Macquarie Valley. Sinclair Knight and Partners Pty., Ltd., Sydney, New South Wales, Australia.

Smith, P., and J. Smith. 1990. Floodplain vegetation. Pages 215–228 *in* N. Mackay and D. Eastburn (eds.), The Murray. Murray Darling Basin Commission, Canberra, Australia.

Stafford Smith, D. M., and S. R. Morton. 1990. A framework for the ecology of arid Australia. *Journal of Arid Environments* 18:255–278.

State of California. 1990. Irrigation water use in the Central Valley of California. California Department of Water Resources, Sacramento, California.

Stephens, D. W., B. Waddell, and J. B. Miller. 1988. Reconnaissance investigation of water quality, bottom sediment, and biota associated with irrigation drainage in the Middle Green River Basin, Utah, 1986–87. Water-resources investigations report 88-4011. US Geological Survey, Salt Lake City, Utah.

Stephens, D. W., B. Waddell, L. A. Peltz, and J. B. Miller. 1992. Detailed study of selenium and selected elements in water, bottom sediment, and biota associated with irrigation drainage in the Middle Green River Basin, Utah, 1988–90. Water-resources investigations report 92-4084. US Geological Survey, Salt Lake City, Utah.

Stevens, T. H., S. Benin, and J. S. Larson. 1995. Public attitudes and economic values for wetland preservation in New England. *Wetlands* 15:226–231.

Stock, R. E. 1978. The impact of the decline of the Hadejia River in Hadejia Emirate. Pages 141–146 *in* G. J. van Apeldoorn (ed.), The aftermath of the 1972–74 drought in Nigeria. Centre for Social and Economic Research, Ahmadu Bello University, Zaria, Nigeria.

Thomas, D. H. L., M. A. Jimoh, and H. Matthes. 1993. Fishing. Pages 97–115 *in* G. E. Hollis, W. M. Adams, and M. Aminu-Kano (eds.), The Hadejia-Nguru Wetlands: Environment, economy and sustainable development of a Sahelian Floodplain wetland. IUCN, Gland, Switzerland.

Thompson, J. R. 1995. Hydrology, water management and wetlands of the Hadejia-Jama'are Basin, northern Nigeria. PhD thesis. University of London, London.

Thompson, J. R. 1996. Africa's floodplains: A hydrological overview. Pages 5–20 *in* M. C. Acreman, and G. E. Hollis (eds.), Water management and wetlands in sub-Saharan Africa. IUCN, Gland, Switzerland.

Thompson, J. R., and G. E. Hollis. 1995. Hydrological modeling and the sustainable development of the Hadejia-Nguru Wetlands, Nigeria. *Hydrological Sciences Journal* 40:97–116.

Thompson, S. P., and K. L. Merritt. 1988. Western Nevada wetlands—history and current status. *Nevada Public Affairs Review* 1:40–45.

Thornton, S. A., and S. V. Briggs. 1994. A survey of hydrological changes to wetlands of the Murrumbidgee River. *Wetlands (Australia)* 13:1–13.

Tréca, B., and S. Ndiaye. 1996. The black crowned cranes in the Senegal Delta. Pages 103–105 *in* R. D. Belilfuss, W. R. Tarboton, and N. N. Gichuki (eds.), Proceedings of the African crane and wetland training workshop, Maun, Botswana, 8–15 August 1993. International Crane Foundation, Baraboo, Wisconsin.

UNEP (United Nations Environmental Program). 1992. Diagnostic study for the development of an action plan for the conservation of the Aral Sea. Unpublished report. United Nations Environmental Program, Nairobi, Kenya, Africa.

Van Ketel, A., M. Marchand, and W. F. Rodenburg. 1987. West Africa review: A comprehensive listing of water management projects and an outline of their effects on wetlands. Edwin Report No. 1. Centre for Environmental Studies, University of Leiden, Leiden, The Netherlands.

Vencil, B. 1986. The Migratory Bird Treaty Act—protecting wildlife on our national refuges—California's Kesterson Reservoir, a case in point. *Natural Resources Journal* 26:609–627.

Vinke, P. P. 1996. The integrated development programme for the left bank of the Senegal River Valley. Pages 145–153 *in* M. C. Acreman, and G. E. Hollis (eds.), Water management and wetlands in sub-Saharan Africa. IUCN, Gland, Switzerland.

Waddell, B. H., and M. C. Stanger. 1992. The influence of selenium on incubation patterns and nesting success of waterbirds at Ouray National Wildlife Refuge, Utah. Contaminant Report R6/400S/92. US Fish and Wildlife Service, Salt Lake City, Utah.

Walker, K. F. 1985. A review of the ecological effects of river regulation in Australia. *Hydrobiologia* 125:111–129.

Wallace, T. 1980. Agricultural projects and land in northern Nigeria. *Review of African Political Economy* 17:59–70.

Wasson, B., B. Banens, P. Davies, W. Maher, S. Robinson, D. Tait, and S. Watson-Browne. 1996. Inland waters. Pages 1–68 *in* N. Alexander and R. Taylor (eds.), Australia: State of environment 1996. An independent report presented to the Commonwealth Minister for the Environment by the State of the Environment Advisory Council. CSIRO Publishing, Melbourne, Victoria, Australia.

WCIC (Water Resources and Irrigation Commission). 1971. Water resources of New South Wales. Government Printer, Sydney, New South Wales, Australia.

Welcomme, R. L. 1985. River fisheries. FAO fisheries technical paper 262. Food and Agriculture Organization, United Nations, Rome, Italy.

Wesseling, J. W., C. A. Naah, C. A., Drijver, and D. Ngantou. 1996. Rehabilitation of the Logone floodplain, Cameroon, through hydrological management. Pages 185–198 *in* M. C. Acreman, and G. E. Hollis (eds.), Water management and wetlands in sub-Saharan Africa. IUCN, Gland, Switzerland.

Whigham, D., D. Dykyjova, and S. Hejny. 1993. Wetlands of the world. I. Inventory, ecology and management. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Whitehead, J. C., and G. O. Blomquist. 1991. Measuring contingent values for wetlands: Effects of information about related environmental goods. *Water Resources Research* 27: 2523–2531.

Whitehead, P. J., and R. Chatto. 1996. Northern Territory. Pages 119–175 *in* A directory of important wetlands in Australia, 2nd ed. Australian Nature Conservation Agency, Canberra, Australia.

Willers, B. 1994. Sustainable development: A new world deception. *Conservation Biology* 8:1146–1148.

Williamson, D. R., G. W. B. Gates, G. Robinson, G. K., Linke, M. P. Seker, and W. R. Evans. 1997. Salt trends. Historic trend in salt concentration and saltload of stream flow in the Murray-Darling Drainage Division. Dryland technical report No. 1. Murray-Darling Basin Commission, Canberra, Australia.

WRC (Water Resources Commission). 1979. Southern Macquarie Marshes water management works: Environmental impact assessment. Rankine and Hill Pty., Ltd., Water Resources Commission, New South Wales, Australia.

WRIC (Water Resources and Irrigation Commission). 1971. Water resources of New South Wales. Government Printer, Sydney, New South Wales, Australia.

Zahm, G. R. 1986. Kesterson Reservoir and Kesterson National Wildlife Refuge: History, current problems, and management alternatives. *Transactions of the North American Wildlife and Natural Resources Conference* 51:324–329.